



MURDOCH
UNIVERSITY

PERTH, WESTERN AUSTRALIA

Solar Collector Efficiency Testing Unit

Thesis Report

ENG460 – Engineering Thesis

A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering.

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11/18/2013

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Acknowledgement

I wish to acknowledge my project supervisors Associate Prof. Graeme Cole and Dr Linh Vu for contributing such great amounts of time, effort and guidance throughout my this project and wider studies over the years. I would also like to thank John Boulton, Will Stirling, and Lafeta 'Jeff' Laava for their technical support throughout the project.

Lastly, a massive thank you must go to my families and friends for supporting me and keeping me sane throughout my journey.

Abstract

This project focuses on the development of the time-efficient Solar Collector Testing Unit in compliance with 'Australian and New Zealand Standard AS/NZS 2535.1:2007'. The prime objective was to modify the existing unit's control and data acquisition system such that experimental parameters were constricted within the bounds quoted by the standard. It is required that the inlet temperature and flow-rate to the solar collector be constrained to an accuracy of $\pm 0.1^{\circ}\text{C}$ and $\pm 1\%$, respectively throughout the 15 minute measurement period. Successful completion of the project objective will allow Solar Collector testing to be conducted in a less time-consuming manner.

The text discusses analysis of factors preventing compliance with the standard, and adjustments to the system responsible for further improving the unit's performance. Steady-state analysis is provided, determining that the violation rate of the flow-rate and temperature outside of the required accuracy bounds has been substantially reduced in comparison to previous iterations of this project.

Significant progress has been made in regard to inlet temperature accuracy, and greater insight has been gained in regard to the inadequacy of domestic water heaters used in the project. It is concluded that without major changes to instrumentation, the unit will not be capable of achieving the bounds set by the standard.

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1. Introduction

Up until relatively recently, fossil fuels have been relatively cheap and easily accessible source of energy when compared to renewable energies such as solar, wind, geothermal, and hydro-electricity. However, growing awareness of the impact of carbon emissions on the global climate and the adverse human health impacts associated with the airborne particulates generated by fossil-fuel combustion (Grigg, 2002) has seen a surge in the development and adoption of technology to harvest renewable energy sources. As the awareness of the importance of climate change has grown, the use of non-renewable fossil fuels has come under increased scrutiny from the scientific community as well as the general public. (Clark, 2013) Heavy reliance on fossil fuels has also resulted in significant increases in the price of these commodities, resulting in fuel shortages and inflation. Continued population and economic growth in developing countries has exacerbated this trend. (Kalogirou, 2004)

There are a number of viable options for renewable energy sources currently available, including solar cells, geothermal technology, hydro-electric schemes, production and combustion of bio-fuels and the harvesting of wind and wave energy. Of these, perhaps the most widely adopted and readily available renewable alternative to fossil fuels is the solar energy.

Solar energy Collectors are an integral part of the solar energy system, harnessing electromagnetic radiation and converting it into heat in the collectors' transport fluid. The transport fluid is usually air, water or oil. The fluid then exits to space conditioning equipment or thermal holding units. In industry and in domestic applications solar collectors are used for electricity generation and water heating. Concentrating and non-concentrating (or stationary) solar collectors are the two main types used. The more sophisticated of the two is the concentrating collector which tracks the sun's movement and features reflective concave interception surfaces that focus the received radiation onto a smaller absorption area, thus increasing the radiation flux, whereas non-concentrating collectors have an equal absorption and interception area. (Kalogirou, 2004)

For the purposes of this project, flat-plate collectors are to be tested by the developed apparatus. Flat-plate collectors are used in water-heating applications, making use of a series pipes residing in a metal absorbing sheet. The sheet is coated black for maximum energy absorption, since less light will be reflected. A transport fluid, water, is continuously forced through the collector's inlet and into the system of pipes where the fluid will be heated by solar radiation. Since the absorption and interception area of the collector are equal, the flat-plate collector is referred to as a non-concentrating type.

Performance of solar collectors is evaluated by "providing a set of performance variables for each solar collector that can be used to determine the heat output under a set of given environmental and operating conditions" (Apricus, 2013). The peak efficiency value is widely used to promote the performance of the collector with factors such as the type and dimensions of the materials used having varied effects. In order to determine the efficiency of solar collectors, it is important to develop a consistent test method. Since power output to the transport fluid can be obtained by observing its change in temperature as it passes through the collector, the temperature and flow-rate of the fluid entering the collector must remain constant throughout the testing process. This requirement has led to the development of the Murdoch University Solar Collector Efficiency Testing Unit (Al Asi, 2012) (Moussa, 2009).

2. Overview of Solar Collector Efficiency Test Unit

The Solar Collector Efficiency Testing unit (SCETU) is currently located in the North-West corner of the Murdoch University Engineering Bayer pilot plant facility. The purpose of developing such a unit was so that testing of Solar Collectors can be conducted in a far less time consuming manner than the previous testing method. The Solar Collector testing apparatus used in the past utilised a rather basic yet effective method of achieving water feed temperature and flow-rate. This involved heating a large quantity of water with a large water vessel over night to the desired temperature. In order to achieve steady flow entering the solar collector, a single control valve was used to manipulate the flow-rate as the water was gravity fed (Moussa, 2009).

The major drawback of such a set-up is that the time necessary to heat the water within the tank to a sufficient level is in the order of hours, and as a result only one test can be conducted each day since it is required for the tank to be heated overnight. Considering that four steady-state tests of four different temperatures are required to complete the solar collector efficiency testing, a maximum of 16 'runs' need to be completed for each Solar Collector.

As a consequence of the time-consuming nature of the current test apparatus efforts became focussed on developing a system where a variety of temperatures and flow-rates could be 'dialled in' and within minutes achieve a water feed that satisfied the proposed outcomes. When it was discovered that achieving a feed which complied with strict guidelines was much more difficult than previously thought, the project was passed down year to year by Instrumentation & Control and Industrial Computer Systems students at Murdoch University.

3. Scope and objective

The primary aim of this project is to design and test the Solar Collector Efficiency Testing Unit (SCETU) such that its performance adheres to Australian and New Zealand Standard AS/NZS 2535.1.2007. These standards provide tight constraints that the unit must operate within; applying to the temperature and flow-rate of the fluid entering the collector, accuracy and resolution of sensors and data logging equipment, and the physical orientation of instrumentation.

The project concerns itself mainly with the control of fluid entering the Solar Collector; hence efforts were focussed on achieving a number of objectives:

- Ensuring consistent performance in the presence of disturbances;
- Enable a user to generate collector inlet flow-rate and temperature of 2-3 l/min and 21-70°C, respectively;
- Maintaining inlet flow-rate within $\pm 1\%$ of desired value;
- Maintaining inlet fluid temperature within $\pm 0.1^\circ\text{C}$ of desired value.

Following the development of a project plan, efforts were focussed on a number of areas in order to achieve the set objectives. Due to the high level of accuracy required by the Australian standard, it was expected that an acceptable level of performance would be achieved once reasonable progress was made in each area of exploration. These areas of exploration included:

- Reducing/removing interference in analogue signals;
- Exploring mixing control valve characteristics;
- Interaction between cold and hot streams;
- Re-evaluation of control valve topology and tuning.

The ultimate reason for choosing to investigate these areas in depth was the limited testing previously done by other students taking on the project. By further understanding the physical interactions between the streams and how data is sent and received, it was expected that greater performance can be achieved.

4. Equipment and Devices

4.1 Physical Devices

- 2 x 50L Rheem water heater/storage tanks
- 1 x Hass Intellifaucet RK250 mixing control valve
- 2 x Endress + Hauser Promag 10H Magnetic flow-meters
- 5 x PT-100 Resistance Temperature Detectors (RTD)
- 1 x DANFOSS MBS 33 pressure transmitter

4.2 I/O Devices

The test apparatus currently makes use of two different distributed I/O systems to manage data acquisition between devices in the field and the PC. In previous iterations of the project National instruments Field-Point systems were solely used due to their availability and capability of handling a large number of analogue and digital signals through the modules described later in this section. According to National Instruments, this system is now obsolete and is therefore no longer available for purchase, instead recommending C series devices i.e. CompactRio and CompactDAQ. (National Instruments, 2013) Due to some concerns surrounding the performance of the Field-Point system, a CompactDAQ system was introduced to work concurrently with the existing I/O. An in-depth discussion of these concerns is included in section 7.1.1.

4.2.1 Field-Point Modules

FP-1000

This module is required to provide communication between the user PC and modules attached to the Field-Point device. The FP-1000 is used to read information from other FP modules and send it via an RS-232 cable to the PC where programs such as the Measurement and Automation Explorer (National Instruments, 2011) and LabView are able process the data. This device also is required to provide power to the adjoining modules, accepting 11-30 VDC, hence a 24V power supply is directly connected to the unit. A user determined data transfer rate of 0.3 kbps, 1.2 kbps, 2.4 kbps, 9.6 kbps, 19.2 kbps 38.4 kbps, 57.6 kbps or 115.2 kbps are possible, although it is recommended that a rate of 115.2 kbps

is selected for fastest performance unless communication problems are experienced.
(National Instruments, 2003)

FP Module	Properties
FP-AI-110	8 channel Analogue input: 4-20mA 500Hz, 50 Hz, 60 Hz noise filtering capabilities Sample rate dependent on filter setting. Application: <i>Mixed stream Temperature, Flow-rate signals</i>
FP-AI-111	16 Channel Analogue input: 4-20mA 500Hz, 50 Hz, 60 Hz noise filtering capabilities Sample rate dependent on filter setting. Application: <i>Tank and stream temperature, pressure sensor signals</i>
FP-AO-200	8 channel Analogue output: 4-20mA and 0-20mA 12 bit Resolution Application: control valve signal output
FP-PWM-520	8 channel pulse width modulator: 5VDC, 12VDC, 24VDC (@ 1Amp) Up to 1kHz (0-100%) Application: Heater Duty cycle signal output

[Table 1 Field-Point Module Properties \(National Instruments, 2003\)](#)

5. Document Review: Test Methods for Solar Collectors (AS/NZS 2535.1.2007)

The document referred to through the entirety of this report outlines uniform test methods, instrumentation specifications and performance criteria regarding thermal performance of liquid heating collectors. The standard is adapted from ISO 9806:1994 and takes into consideration Australian and New Zealand conditions which vary to those found internationally. The following sections discuss portions of document AS/NZS 2535.1.2007 that are thoroughly explored as a means of achieving the project objectives. Portions of the document which have purposely not been explored have been explicitly stated.

5.1 Instrumentation

There are specific guidelines regarding the accuracy of measurements taken via the supervisory control and data acquisition (SCADA) system. These measurements refer largely to temperature and flow-rate measurements about the test apparatus and make mention of accuracy, resolution and mounting position.

Three temperature measurements are required:

- Ambient air temperature ;
- Transport fluid temperature at the collector inlet;
- Transport fluid temperature at the collector outlet.

An accuracy of 0.1°C in the temperature measurement is required with a resolution $\pm 0.02^\circ\text{C}$ to ensure that the temperature does not drift over the testing period. The 12-bit digital system used throughout the system is capable of this resolution. The fluid inlet temperature sensor must be mounted within 200mm of the collector inlet and be adequately insulated to ensure that heat loss is minimal.

The quantity of transport fluid entering the collector is to be measured in terms of mass flow-rate, but can also be determined by the relationship between volumetric flow-rate and inlet temperature. This is required as the density of the fluid changes with temperature;

hence a volumetric flow-rate of 3l/min at 25°C and 70°C will differ greatly in terms of mass. The flow-rate measurement must be taken with an accuracy of $\pm 1\%$.

Calibration and accuracy regarding wind speed, pressure drop, ambient air temperature and solar radiation measurement devices have not been explored and lie outside the scope of this project.

5.2 Mounting and location of Collector

At no point throughout the project was the Solar Collector Efficiency Testing Unit physically connected to a Flat-Plate Collector or any other type of solar collector, due to a focus on meeting a specific set of objectives not including actual solar collector testing. For this reason there has been no need to meet requirements regarding collector location, mounting methods, wind and solar radiation sensor position or environmental factors such as ambient air temperature and wind.

5.3 Recommended Test installation

Within the document examples of possible open-loop and closed-loop test installations are discussed (Standards Australia, 2007). These methods are similar to those used previously by the Murdoch University for solar collector testing and deemed extremely time consuming, hence the development of the new testing unit which is the subject of this report.

5.4 Test conditions and procedure

The document recommends that a fluid mass flow-rate of 0.02 kg/s per square meter of the collector's gross area be used for testing, unless otherwise recommended. It is suggested by Dr Trevor Pryor, senior lecturer of Environmental Engineering at Murdoch University, that flow-rate between 2 kg/min and 4 kg/min be provided by the testing unit. Further information regarding solar irradiance and wind speed criteria are also included in the document.

It is recommended that at least four different inlet fluid temperature data points be taken over the operating range of the collector. One data point must be taken within $\pm 3^\circ\text{C}$ of the

ambient air temperature as a determination of η_0 . A maximum temperature of 70°C is recommended but not required.

Nowhere within the standard is it stated that the hot and cold stream supply tanks take on any specific temperature or adhere to any deviation limit. This is because no test installation using a blended stream has been used before and has no mention in the standard. For this reason, the user is entitled to set the hot and cold stream supply tank to any values which provides an inlet flow-rate and temperature in compliance with the performance criteria.

5.5 Definition and Interpretation of Steady-state operation

In the past there has been some ambiguity regarding the wording used in section 8.6 of the standard. The document states:

“A collector is considered to have been operating in steady-state conditions over a given measurement period if none of the experimental parameters deviate from their mean values over the measurement period by more than the limits given in table 1 (see Table 2). To establish that a steady-state exists, average values of each parameter taken over successive periods of 30 seconds shall be compared with the mean value over the measurement period.” (Standards Australia, 2007)

Parameter	Deviation
Inlet Flow-rate	±1%
Inlet Temperature	±0.1°C

Table 2 Experimental Parameter Deviation Limits

One interpretation of the statement is that no single measurement may fall outside the limits presented in Table 2. That is, if the inlet fluid flow-rate were to exceed these limits for one measurement interval this would be deemed to be a failure of the steady-state condition. This is an incredibly strict condition, as a minor violation of the limit such as exceeding the flow-rate limit by 5mL/min for a 5 second period has no noticeable effect on the quality or accuracy of the test results. By adopting this interpretation, it renders the following sentence regarding successive 30 second averages throughout the measurement period void.

It is believed that the ambiguity of this statement lies in what is meant by the phrase *“if none of the experimental parameters deviate from their mean values... by more than the limits given...”* (Standards Australia, 2007)

The definition of a parameter is “a numerical factor forming one of a set that defines a system” (Merriam-Webster, 2013). In the context of the document, experimental parameters refer to the factors which may be altered from test to test in order to determine how solar collector’s efficiency is affected. At no point is it stated or implied that the term ‘experimental parameter’ refers to individual samples from the experimentally obtained data series.

The averaging of values within 30 second periods and comparison with the mean value over the entirety of the measurement period is a much more sensible method of determining the steady-state operation of the testing unit. Due to a maximum sample time of 1 second and the time constants involved in the heating process within the collector being in the order of hours not seconds, it is believed that any performance affecting violations in inlet flow-rate or temperature will be picked up by the averaging process.

Depending on the interpretation of the ‘steady-state testing requirements’ it may be declared that the performance criteria, in terms of inlet flow-rate and temperature, have been met. An interesting point to note is that in the past the second interpretation of steady-state operation has been met (Standards Australia, 2007), yet the ambiguity of the statement within the AS/NZS 2535.1.2007 document has resisted confidence in the performance of the SCETU.

6. Project History

In 2006, Phil Minnisale and Huang Jian developed the original SCTU which mixes two streams of water with different temperatures sourced from separately heated tanks (Jian, 2006). This method achieves inlet flow-rate and temperature values close to those required for testing by manipulating the magnitude of flow exiting each heating vessel. Unfortunately, this system was inadequate at supplying $\pm 1\%$ accuracy for flow-rate and $\pm 0.1^\circ\text{C}$ for temperature. Although unable to meet the standards requirements, Minnisale and Jians' work formed a foundation upon which further developments were to be made.

Figure 1 shows the schematic diagram of the Solar Collector Testing unit up until 2009 when Hany Moussa introduced a number of important changes to the unit (Moussa, 2009). The unit consists of two streams (hot and cold) fed from a designated heated water tank fitted with a circulation pump for mixing purposes. The heating tanks are also each fitted with a temperature sensor which is used exclusively for temperature control of fluid within the vessel. The two control valves are used to independently alter the stream flow-rates in accordance with instructions from a custom-made interaction-decoupling block (Moussa, 2009). Each stream is mounted with a flow meter and temperature sensor which acquires process information to be used in the decoupling control strategy and data logging. A fifth temperature sensor is used to measure the temperature of the mixed stream and is fitted after the mixing valve. Due to the absence of a flow meter on the mixed stream, the sum of the measurement from the hot and cold stream flow meters is taken to be the final mixed flow-rate.

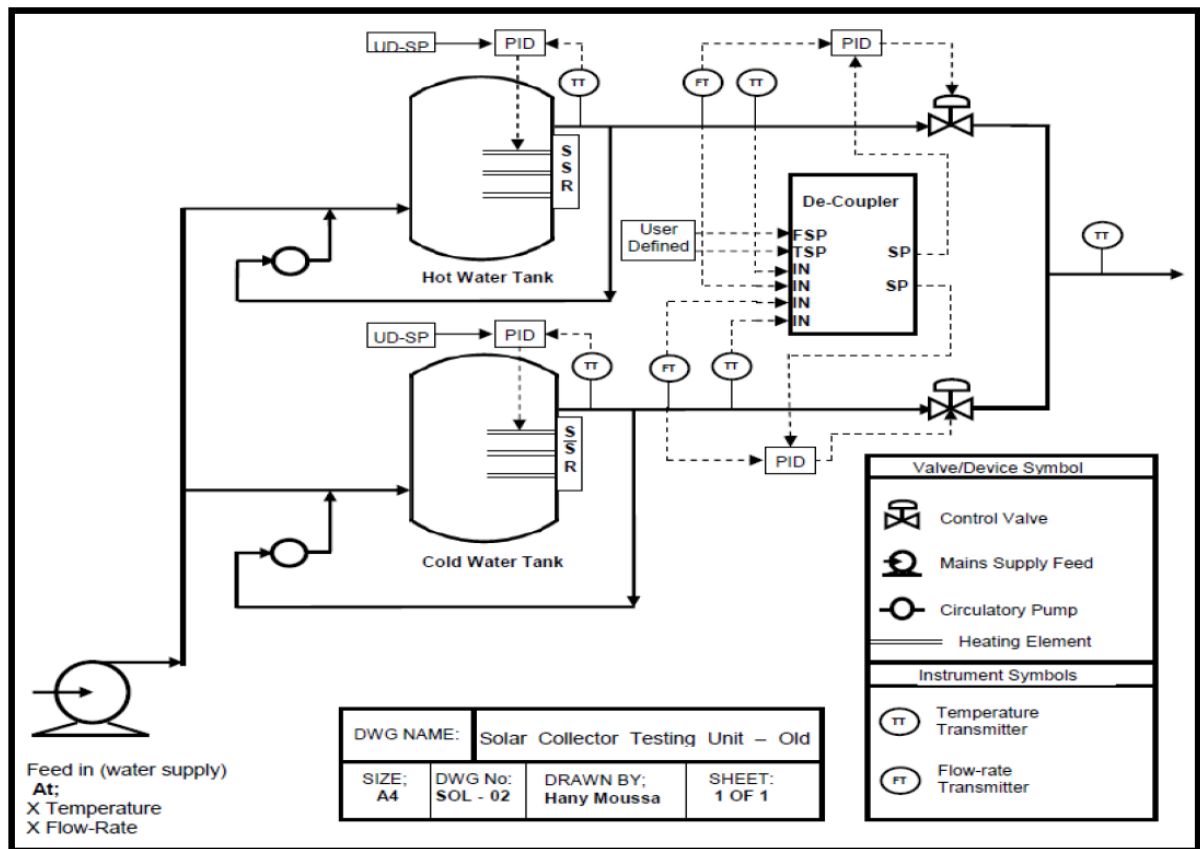


Figure 1 Previous Project Model (Moussa, 2009)

6.1 Decoupling Process Interactions

The process being controlled in this project is a typical blending system, where two streams of varying temperature and flow-rate are mixed to obtain a final product (Ogunnaike, 1994). Since the purpose of the unit is to 'dial-in' a final mixed flow-rate and temperature, the system has two output (process) variables. Manipulation of the hot and cold stream results in changes in the output variables; hence these are the input (manipulated) variables, making the blending system a two input-two output system. When working with multiple input-multiple output (MIMO) systems it is important to pair input and output variables in control loops such that loop interactions are minimised (Ogunnaike, 1994). Relative Gain Array (RGA) analysis indicates that both the hot and cold stream flow-rates have an equal effect on the final mixed flow-rate and temperature (Ogunnaike, 1994).

6.1.1 Values Method

Equation 1 and Equation 2 show the relationship between the hot and cold stream flow-rate, F , and Temperature, T . Subscripts 'C', 'H' and 'M' refer to the cold, hot and mixed streams, respectively. From these equations it is apparent that loop interactions are inevitable without proper decoupling. As a means of reducing interactions in the final flow-rate and temperature of fluid exiting the unit, a customised decoupling block, called the Values method, was designed and implemented by Hamad Al-Senaid in 2007. (Al-Senaid, 2007) This interaction decoupling method rearranges the blending system equations and allows the specific stream flow-rate, $F_{H,SP}$ and $F_{C,SP}$, to be calculated based on the desired mixed flow-rate, F_{SP} , and temperature, T_{SP} , and the temperature of each stream, T_H and T_C (Equation 3 and Equation 4).

Blending system balance:

$$F_C + F_H = F_M \quad (1)$$

Final Mixed Flow-rate

$$T_C F_C + T_H F_H = F_M T_M \quad (2)$$

Final Mixed Inlet Temperature

Set-point calculation for cold stream flow-rate (Values Method):

$$F_{C,SP} = F_{SP} \frac{T_H - T_{SP}}{T_H - T_C} \quad (3)$$

Cold Stream Flow SP (values)

Set-point calculation for hot stream flow-rate (Values Method):

$$F_{H,SP} = F_{SP} \frac{T_{SP} - T_C}{T_H - T_C} \quad (4)$$

Hot Stream Flow SP (values)

The calculated stream set-point is then sent to the streams' respective PID controller, where the control valve position is manipulated to obtain the desired flow-rate. Provided that these PID controllers are able to accurately regulate the stream flow-rate, this is a highly

effective method of interaction decoupling. The drawback of this method is that heat loss in the pipes causes a temperature offset between the measured mixed temperature and the set-point. (Gvozdenac, 2008) In order to remedy this problem, Hany Moussa introduced a temperature offset controller which proportionally readjusted the hot and cold stream flow-rates such that any offset in temperature was removed.

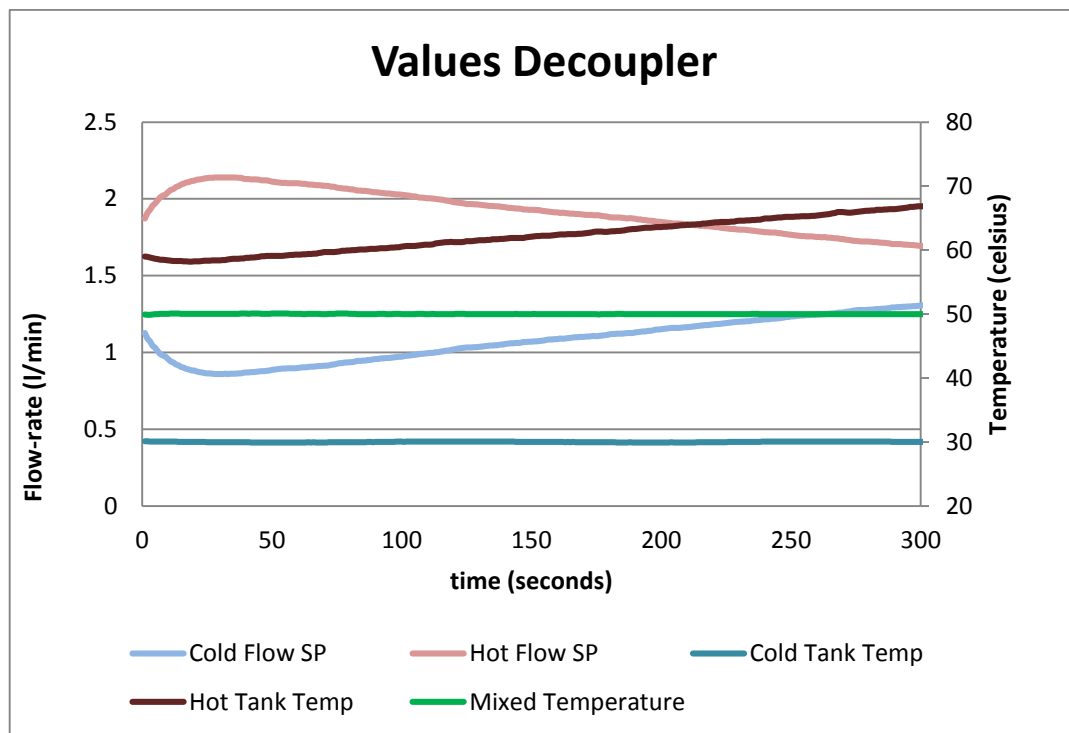


Figure 2 Example of Values Decoupler correcting drop in stream temperature

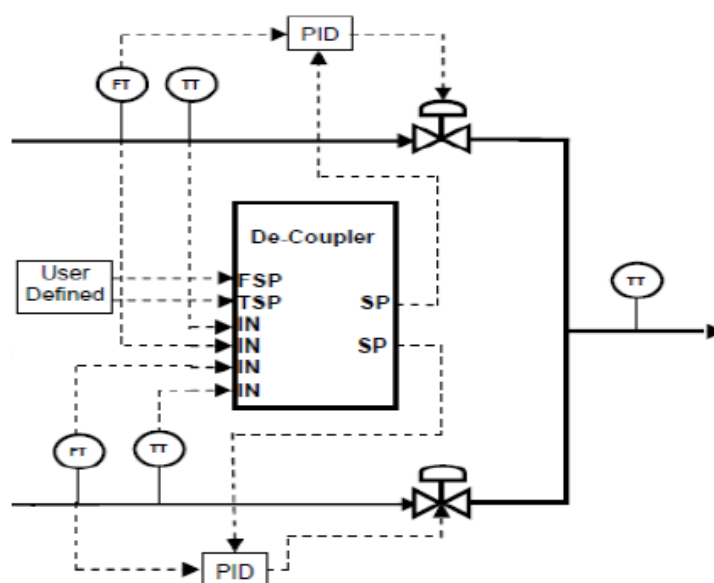


Figure 3 Values Decoupler Block

6.1.2 Percentage Method

In 2012, Amer Al Asi re-visited the formulation of the decoupling strategy, believing that the temperature offset controllers could be removed if key changes were made to the decoupling algorithm. The new arrangement, the Percentage method, does not rely on the decoupler sending hot and cold stream flow-rates to the PID controllers; rather the PID controllers directly monitor the process variables. The output from the controllers is then passed into the decoupling block where the algorithm calculates a percentage flow-rate for each stream.

Equation 5 and Equation 6 show the algorithm used within the percentage method decoupling block. The terms F'_{SP} and T'_{SP} are not the user-defined set-points, rather they are outputs from the respective PID controllers responsible for temperature and flow-rate control. Note that the measured stream temperatures are omitted from calculations since it is desired for calculations to be in terms of percentages. The reasoning for this as stated by Al Asi,

“To change the decoupler’s algorithm so that it only uses percentages, the temperature of the hot stream was assumed to be 100%, since it is kept at the maximum temperature that can be drawn from the unit. Similarly the temperature of the cold stream was assumed to be 0%, since it is kept at the minimum temperature that can be obtained by the unit.” (Al Asi, 2012)

$$\%F_{H,SP} = F'_{SP} \frac{T'_{SP}}{100} \quad (5)$$

Hot valve opening (percentage)

$$\%F_{C,SP} = F'_{SP} \frac{(100 - T'_{SP})}{100} \quad (6)$$

Cold Valve opening (percentage)

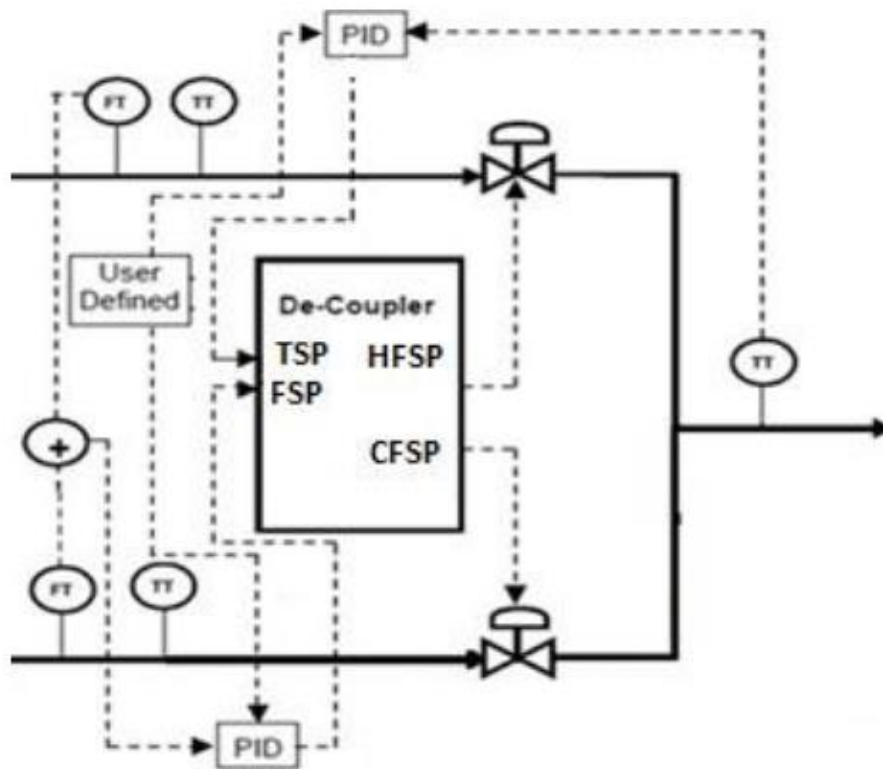


Figure 4 Percentage Decoupler Block

The use of the percentage decoupler is not investigated in this report due to the inability to achieve any function from it, meaning that the Percentage method is not practicable. When operation was attempted with a program provided from 2012, the stream flow-rates oscillate out of control, making the implementation of such a controller questionable.

6.2 Previous Results

6.2.1 Previous Testing of Heating Units

In 2009 and 2012, tests were conducted in order to determine whether the hot water unit in particular was able to satisfy an output of 70°C at 3 l/min.

Hany Moussa came to the conclusion that:

“... having the pump turned on did not allow the heater enough time to concentrate its energy on a specific volume of water, but rather add its heat over multiple stages as the flow was constantly being circulated. Therefore, the implication of having the circulation

pump switched on will cause the effect of the disturbance to occur much faster than if the pump simply was not activated.” (Moussa, 2009)

According to this statement, in order to maintain the hot water tank’s temperature above 70°C it is recommended to conduct tests with the tanks circulations pumps disabled and the heating element duty cycle kept at 100%. 3 years later Amer Al Asi also conducted his own experiments on the heating system and came to a similar conclusion, finding that for an inlet flow-rate of 3l/min a maximum steady state temperature of 65.5°C is obtained with the heating element at maximum output. (Al Asi, 2012) The validity of these results and solutions to issues raised in past iterations of the project will be addressed in section 7.5.

6.2.2 Steady-state Testing

In 2009, Hany Moussa carried out a series of tests using the Values method discussed in section 6.1.1 to decouple process interactions and EPV-250B proportional control valves to perform stream flow-rate regulation. The use of the proportional control valves provided vastly improved results compared to those collected by Hamad Al-Senaïd in 2008. Al-Senaïd made use of the same decoupling method, although Fisher Baumann 51000 valves (Emerson Process, 2012) were utilised. Table 3 shows a number of statistics used to quantify the performance of the unit as performed by Al-Senaïd and Moussa. Unfortunately, the same mixed temperature set-point was not used for both test sequences so full comparison of these results cannot be made.

The main reason for Moussa to introduce EPV-250B valves was due to the ‘stickiness’ experienced by the Fisher Baumann 51000 valves. The ‘stickiness’ refers to the delay between the control action being sent to the valve and the actual physical repositioning of the valve stem. It was believed that the large number of ‘violations’ (experimental values deviating outside the set limits) experienced was caused by this imprecise valve movement. It is shown in Table 3 that the ranges of the experimental values are greatly reduced between 2008 and 2009 due to the replacement of the valves. Also, note the increased accuracy in regards to steady-state inlet temperature: the 2008 mean for the entire measurement period deviates from the set-point by approximately 0.12°C, whereas results from 2009 show that the deviation from mean is negligible.

Al-Senaid (2008)		Al-Senaid (2008)	
Steady state flow-rate at 55°C		Steady state temperature at 55°C	
Mean	3.002115	Mean	54.8778
Mode	2.997	Mode	54.886
Standard Deviation	0.026968	Standard Deviation	0.108557
Min	2.937	Min	54.597
Max	3.101	Max	55.372
Range	0.164	Range	0.775

Moussa (2009)		Moussa (2009)	
Steady state flow-rate at 45°C		Steady state temperature at 45°C	
Mean	2.999	Mean	45.006
Standard Deviation	0.018	Standard Deviation	0.1
Min	2.94	Min	44.729
Max	3.037	Max	45.239
Range	0.097	Range	0.51

Table 3 Previous Results (Moussa, 2009)

Results from 2009 indicate that steady-state operation in compliance with AS/NZS 2535.1.2007 is possible when evaluating data over the experimental data using the 30 second averaging method. Failure to meet compliance with the stricter interpretation has allowed the continuation of research into the system.

Replacement of the EPV-250B valves with the Intellifaucet RK250 mixing control valve (Hass manufacturing company, 2013) in 2012 is believed to have greatly improved the performance of the unit, due to the increased precision of the stepper-motor adjusted device. The introduction of the Percentage decoupling method was also shown to drastically improve the inlet flow-rate control, yet the persistence of out-of-specification measurements was cause for further investigation. There are a number of concerns regarding the validity of the results obtained in 2012, due to the absence of graphs displaying data over the full 15 minute test period (900 data points expected), omission of statistical analysis, and flaws in the LabView Program used. This has prevented comprehensive comparison between past and current performance of the unit.

7. Project Adjustment

7.1 Intellifaucet RK250 Mixing Valve

A key objective of this project was to improve the performance and increase understanding of the RK250 mixing valve. (Hass manufacturing company, 2013) This included investigating the relationship between valve position and stream flow-rate, stream interactions, and refining the stepper motors drivers and signalling. The following sections discuss complications with the RK250 which have been shown to negatively impact on the control scheme's performance.

The Intellifaucet RK250 mixing valve was first introduced by Amer Al Asi in 2012 in order to achieve more accurate stream flow-rate control. Previously there had been a lot of difficulty in maintaining the stream flow-rates such that they did not exceed the specified bounds of $\pm 1\%$ of the final flow-rate. The RK250 was expected to enable more precision in the movement of the valves stem as a stepper motor is used to complete the actuation, rather than pneumatic actuation which can be susceptible to hysteresis.

The stepper motors contained within the mixing valve unit were originally designed to receive pulse sequences responsible for driving the motor from an onboard microcontroller. The onboard controller was able to control temperature and flow-rate via instructions produced by a preloaded control algorithm. Limitations in the accuracy of flow-rate control caused the onboard controller to be replaced with an external 68HC12 microcontroller. (Rosenberg, 2000) Al Asi, with assistance from Assoc. Prof. Graeme Cole and Mr Jeff Laava, was able to successfully introduce the 68HC12, although it was believed that further research and experimentation would ultimately result in compliance with standard AS/NZS 2535.1.2007.

As a result of introducing the external microcontroller greater flexibility is given to the programmer. Not only can a custom control scheme be used to control the flow-rate and temperature, but the program required to convert control actions to a step sequence can also be manipulated.

7.1.1 Signal interference - 'jitter' and 'spiking'

The 68HC12 microcontroller is responsible for analogue to digital conversion that allows the 0-20mA current signal sent from the AO-200 module to be converted into a 10-bit value. The 10-bit value is then scaled into a number of steps to be executed by the stepper motor. Since the performance of the control valves is heavily dependent on the ability of the stepper motor to execute the desired number of steps, it is important that the quality of the signal sent to the microcontroller experiences minimal interference.

Concerns about the quality of the current signal sent to the microcontroller were raised when it was observed that movement in the stepper motors position occurred, even when a constant 0-20mA signal was sent. The constant deviation of ± 4 steps from the desired point, along with intermittent jumps of up to 8 steps resulted in poor flow-rate control. The undesired movement in the stepper motor is referred to as 'jitter' and 'spiking' throughout the remainder of this report. A number of possible causes of this 'jitter' were hypothesised with 50Hz interference seeming to be the most likely culprit. In order to eliminate the interference the following modifications were made to the Field-point/68HC12/RK250 configuration:

- Physical separation of AC powered devices and cable from small signal wiring;
- Shielding of small signal wires;
- Addition of a low pass RC filter to control valve current signal wires entering 68HC12.
($R = 100k\Omega$ $C = 10 \mu F$);
- Isolation of 68HC12 power supply from other powered devices.

Even with these modifications 'jitter' and 'spiking' persisted, although a reduction in magnitude was observed. Consultation with National Instruments technical staff Jayson Kok, led to the decision to replace the existing Field-point AO-200 analogue output module with the higher specification CompactDAQ NI-9265 AO module. It was believed that the CompactDAQ device would be capable of producing a 'less noisy' analogue signal, due to increased update rate, 16-bit digital-to-analogue conversion and isolation from other field input and output devices which contribute to interference.

It was observed that the signal was more susceptible to interference and experienced greater fluctuations in voltage at the microcontroller input terminals prior to the modifications and AO device replacement, as a peak-to-peak (pk-pk) interference band of 28mV was present before and 10mV pk-pk after. This resulted in the 'jitter' being reduced from ± 4 steps to ± 2 steps, and 'spiking' completely eliminated.

After replacing the Field-Point analogue output device with CompactDAQ NI-9265 it was observed that the unit was better able to provide a voltage signal that could supply the 68HC12 microcontroller with the full 0-5V range required. Previously, the AO-200 module was limited to a current output equivalent to 2.2V when passed through the pre-existing RC filter circuit. The current supplied by the NI-9265 module allowed a maximum voltage of 5V through the addition of a 670Ω resistor installed in parallel with the microcontroller input terminals. This greater voltage range prevented the control signal from being masked by the remaining signal interference.

7.1.2 Stepper motor (Forth) program modifications

In order to further reduce the effects of interference and limit the valve position to the 'useable' range, modifications were made to key parameters in the stepper motors A/D conversion and driver program settings. The program loaded onto the 68HC12 external microcontroller is responsible for developing the step sequence sent to the control valve stepper motors. The analogue signal is converted into a digital value, which is scaled to give the number of steps to be executed. Therefore a number of user-defined parameters have been formulated to further improve the performance of the mixing valve.

There are 5 main parameters that may be adjusted:

'LeftSteps' and 'RightSteps' – Represents the maximum possible number of steps executed by the stepper motors. This parameter can take any positive integer value less than 1130. The tags Left and Right refer to the cold stream and right stream control valves, respectively.

‘AnalogLoopTime’ – The time taken to sample analogue signal and perform A/D scaling. If the loop time is too fast there will not be sufficient time for the motors to execute the desired number of steps being requested.

‘AdjustLimit’ – This parameter determines the maximum number of steps which can be executed in one sequence. The time taken to perform a single step and the loop time can be used to help in the selection of this parameter, ‘AnalogLoopTime’/‘StepTime’.

‘MaxResult’ –This parameter is the maximum digital value which can be obtained through A/D conversion based on the voltage range ‘seen’ by the microcontrollers input port. By default, A/D conversion of the microcontroller expects a 0-5V analogue signal which is to be converted to a 10-bit value, 0 to 1024.

7.2 Valve Characteristic

In past iterations of the project, students have had issues with obtaining a sufficient degree of accuracy when controlling the water flow-rate through the hot and cold fluid through their respective streams. Hany Moussa proposed the use of new valves which have a linear flow characteristic and zero hysteresis. The Intellifaucet RK250 mixing valve was found to be a viable replacement for the pre-existing EPV-250B proportional valves which gave inadequate performance due to their slow response.

For unknown reasons, thorough testing of the RK250’s has not been previously carried out. It is important to understand the characteristics of control valves as the performance of the entire control scheme is dependent on execution of control actions accurately representing those expected by controllers. Failure to do so will result in poorly tuned control loops for certain areas of operation if non-linearity characteristics dominate the system.

7.2.1 ‘Useable’ Valve Range

The control valve unit was found to have a total of 1120 steps available on the cold stream valve motor and 1130 on the hot stream valve motor. Therefore executing this number of steps would cause the valves to become fully open. Early tests showed that opening the valve by more than 500 steps gave no further increase in volumetric flow-rate for each

stream when operated individually (with the other closed). Similarly, no further increase in flow-rate was observed when both stream control valves were opened more than 456 steps simultaneously. It was also found that for 0-70 steps for the cold stream and 0-90 steps for the hot stream control valve the volumetric flow-rates remained at 0 l/min. Thus making the 'useable' range for the cold and hot stream control valves 70 to 456 and 90 to 456 steps, respectively.

Previously, any value above approximately 40% sent by the PID controllers to the control valves had no effect on the flow-rate of either stream. By limiting the valve to its 'useable' range flow-rate control is vastly improved since any manipulation of the valve position is guaranteed to cause a change in the process variables.

7.2.2 Step Testing and Stream Interaction

Testing of control valves in the past has mainly occurred in isolation, that is, where only one valve is manipulated whilst the other remains closed. This does not fully represent what is actually experienced whilst the SCTU is operation as interactions occur between the two streams when mixing takes place. For this reason, step tests were carried out on valve 'A' whilst valve 'B' adhered to two different conditions.

STEP TEST conditions*:

1. Valve 'B' fully-closed such that 0 l/min flow-rate is recorded.
2. Valve 'B' remains at a constant valve position.

**Valve 'A' denotes the valve which is currently being tested, that is, the valve that is being stepped at fixed time intervals. Valve 'B' is the valve which is to occupy either a fixed or variable state depending on the condition required by the specific test.*

Based on the 'useable range' of the control valves, the stepper-motor driver program has been altered such that a maximum of 456 steps constitutes as 'fully-open' or 100% for both stream control valves. The absence of flow within 0-15% for both valves was deemed not to be a cause for concern and did not result in any adjustment to driver program. This is due to the regular area of operation for both streams to be in the range of approximately 55-100%.

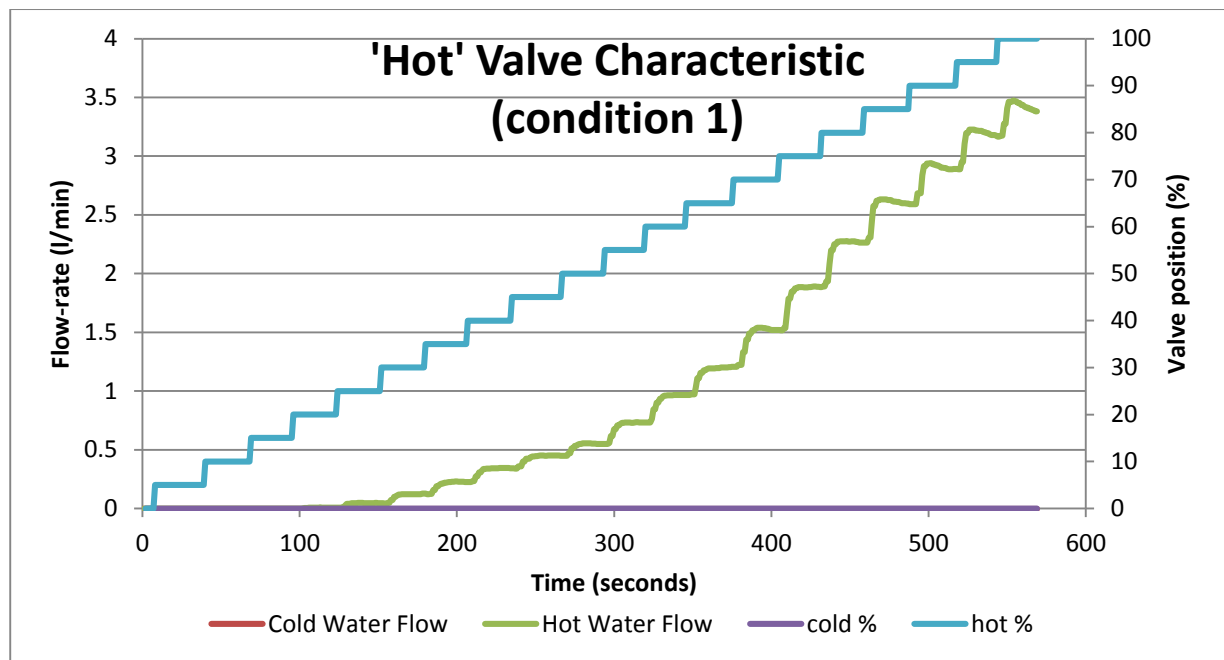


Figure 5 Hot Valve Characteristic (condition 1): pressure head effect

The flow characteristic of the hot stream in Figure 5 shows two distinct areas, one between 20-50% where +1% corresponds to an increase of 20ml/min and the second where +1% relates to an increase of 56 ml/min. The cold stream under condition 1 (Figure 7) does not exhibit this phenomenon. This indicates that the pressure drop across the valve is substantially lower than that in the cold stream. It is believed that this is as a consequence of the elevation of the cold water supply tank being 3-feet more than that of the hot supply tank, causing a noticeable difference in head pressure

To further investigate this phenomenon, a 2.5% step increase in valve position was executed in the hot stream after an open-loop flow-rate of approximately 1 l/min had been established. In order to compare the system at a higher flow-rate region, the same test was carried out after an open-loop flow-rate of 2 l/min was established. The step responses were logged and modelled by a first-order transfer function with the use of Microsoft Excel Solver, Equation 7 and Equation 8. By observing the difference in process gain, 0.032 (lower) and 0.062 (upper), it can be concluded that the presence of this phenomenon will have an effect on the performance of the PID controllers in these separate areas of operation.

$$g(s)_H = \frac{0.032e^{-s}}{1.14s+1} \quad (7)$$

Hot Stream flow model (lower region)

$$g(s)_H = \frac{0.062e^{-s}}{1.14s+1} \quad (8)$$

Hot Stream flow model (upper region)

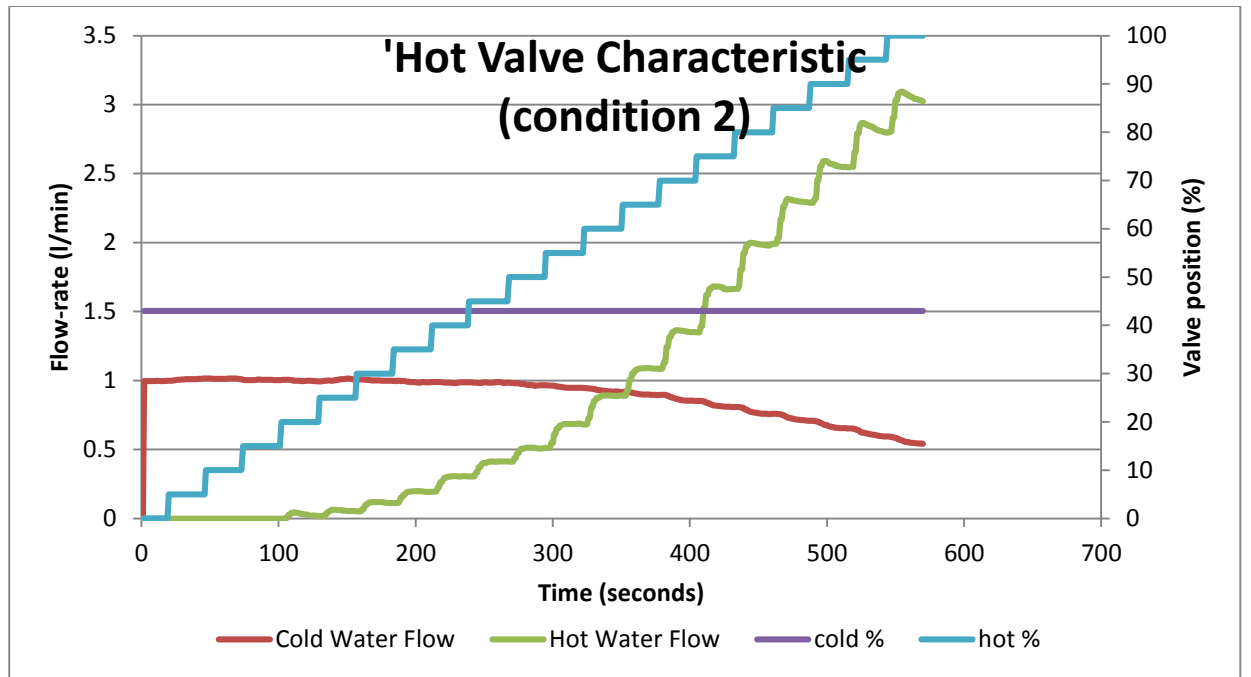


Figure 6 Hot Valve Characteristic (condition 2): pressure head effect

Observe that as the Valve “A” position increases in condition 2, the flow-rate in stream “B” gradually decreases as the valve position exceeds 50%, in Figures 6 and 8. This is as a result of the stream interaction where by backpressure is created in the opposing stream. Note that, for valve positions above 50%, the step response in flow-rate exhibits a second order characteristic due to the interaction. This further complicates the tuning required for the stream controllers.

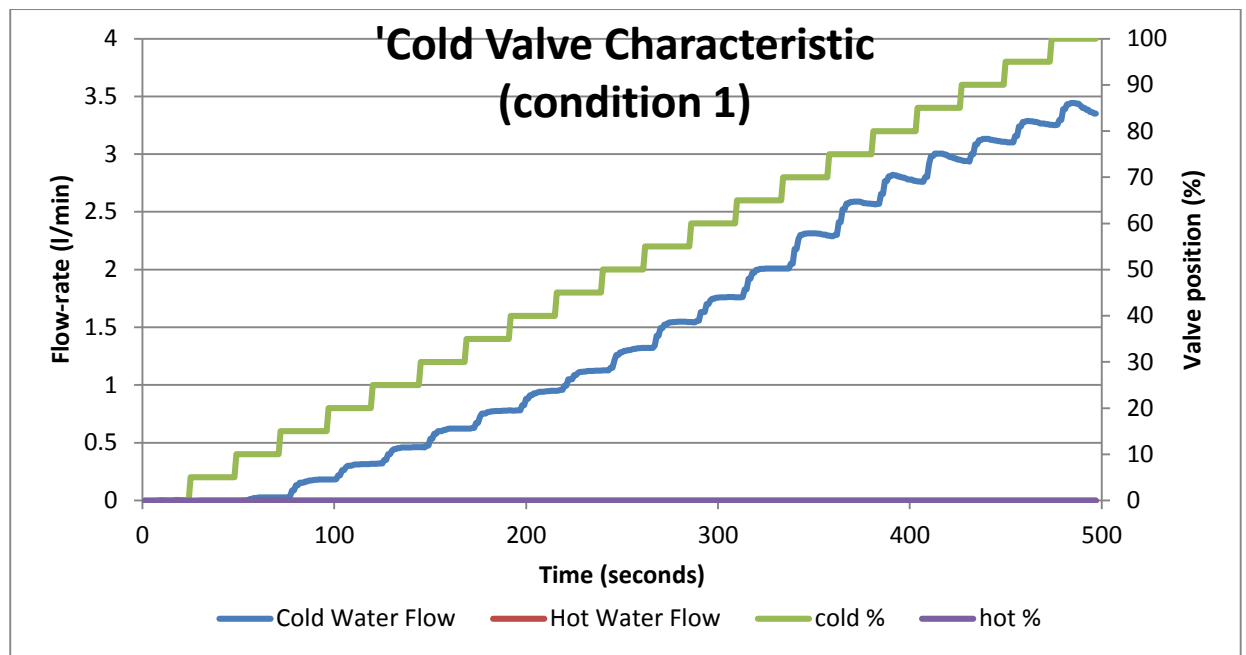


Figure 7 Cold Valve Characteristic (condition 1)

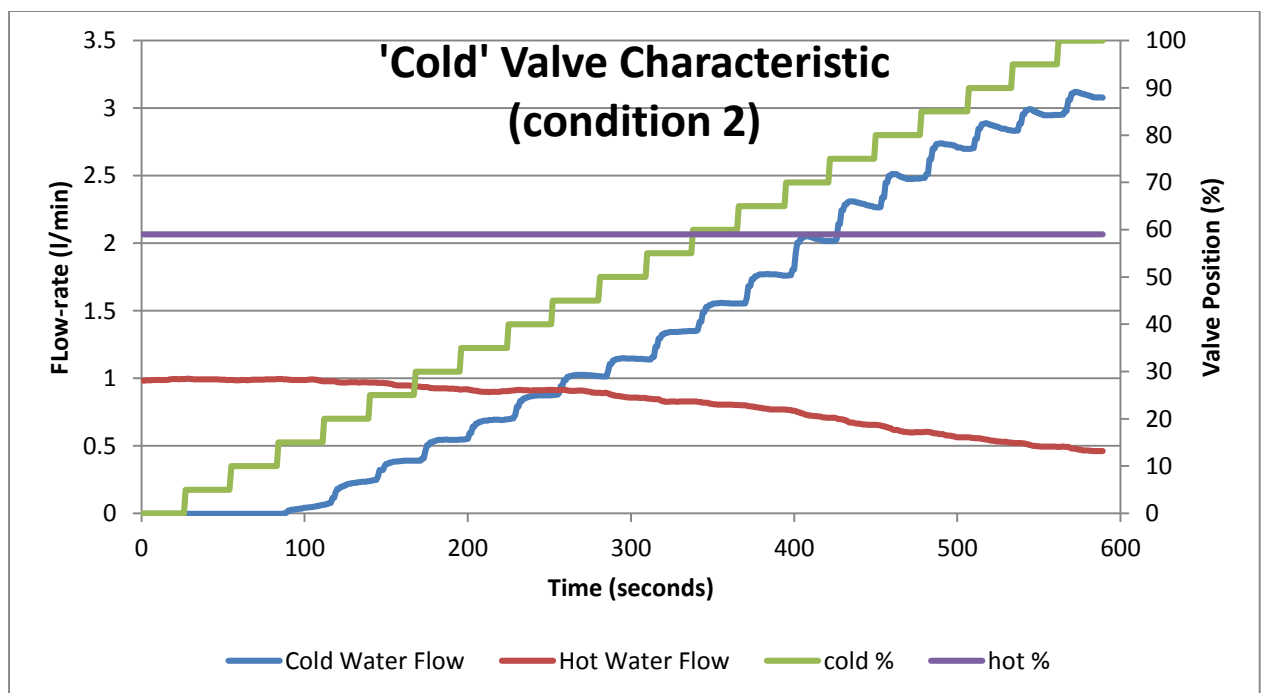


Figure 8 Cold Valve Characteristic (condition 2)

7.3 Open Loop Disturbance and Pressure Sensor

When the respective valves for the hot and cold streams are left at a fixed position, fluctuations in the flow-rate are observed. This was previously believed to be due to interference in the flow-rate measurement signal. Figure 9 shows that the same fluctuation

is present in both streams at the same time. It is difficult to ascertain whether it is a result of interference or due to the mains supply pressure fluctuation.

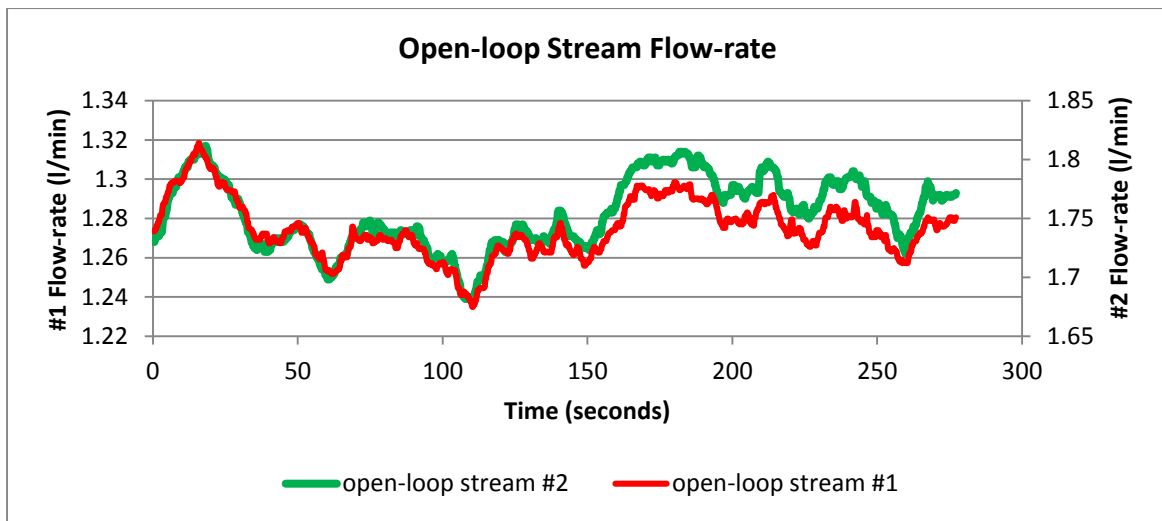


Figure 9 Open-loop Stream Flow-rate

Figure 10 shows the results of closing one loop and leaving the other open. The manipulated variable (control valve position) for the closed-loop is also displayed. It is observed that the MV 'mirrors' the fluctuation in the open-loop measurement, whilst the disturbance is rejected from the closed-loop stream. This indicates that the fluctuation is caused indeed by fluctuation in supply pressure and not a result of noisy signals.

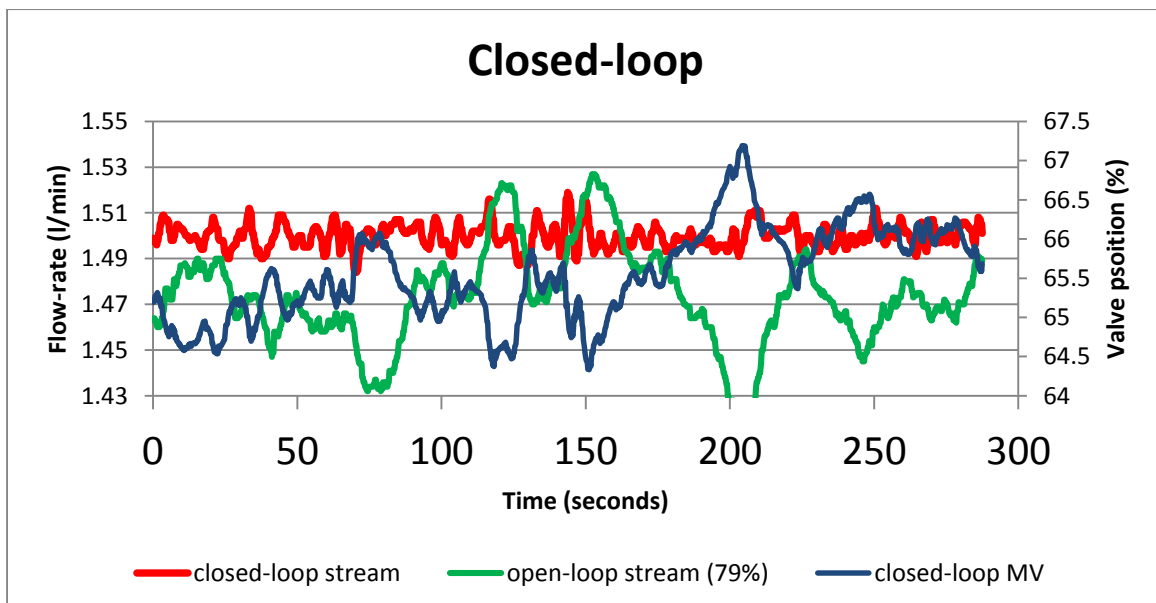


Figure 10 Rejection of mains supply pressure disturbance

7.4 Tuning Stream Flow-rate PID controllers

The tuning parameters used by Al Asi in 2012 were developed in accordance with the percentage decoupling method and the stepper motors using their maximum range of 1130 steps, and therefore differ greatly to those used in this study. The PID controllers responsible for hot and cold stream flow-rate control were re-tuned with the addition of a previously omitted derivative term, K_D . In past iterations of the project only the proportional and integral gain terms were used in the controller algorithm. Through analysis of the effect of the supply pressure disturbance on the flow-rate and the ability of the control action to reject it, it was observed that the flow-rate would consistently overshoot the set-point. The addition of the derivative gain term was to reduce the overshoot, effectively increasing the 'speed' of the system by improving the settling time and stability of the system. Comparison with previous tuning parameters with K_D omitted showed that using all three terms provided the best performance with the individual stream flow-rates exhibiting substantially less overshoot, as seen in table 9 in section 8.3.

Since a maximum valve position of 456 steps yielded the highest possible flow-rate for both valves, this was set as the valves' 'useable' range. By reducing the number of steps possibly executed by the valve, the valves' flow characteristic was also affected, requiring the tuning of the PID controller to be re-evaluated. The Ziegler-Nichols approximate model PID tuning method (Ogunnaike, 1994) was used to estimate the PID tuning parameters, although trial-and-error was ultimately required to refine the performance of the controllers. The PID controller values used for steady-state performance testing are displayed in table 4.

Parameter	Cold stream Controller	Hot Stream controller	Temp offset controller
Proportional Gain	15	16	20
Integral time (min)	0.02	0.015	0.05
Derivative time (min)	0.008	0.002	N/A
Loop-time (ms)	150		

Table 4 Stream Flow-rate PID control parameters

The hot and cold stream valves had different flow characteristics due to the additional height of the cold water supply tank causing an augmented pressure drop compared to the lower hot supply tank. This affected the performance of the control valves within various

ranges of operation, particularly at flow-rates below 1.5l/min. In spite of this the same tuning parameters were used for all final flow-rate and temperature set-points.

7.5 Water Heater/Storage Unit Temperature Control

In past iterations of this project there has been scrutiny of the Rheem hot water system's ability to sufficiently maintain stream temperatures in compliance with the AS/NZS standard. The standard suggests that inlet temperatures of 70°C be tested with an inlet flow-rate of approximately 3 l/min, although this is not a requirement. Previously it was assumed that the heated supply tanks must be set to rigid temperature set-points and may not deviate from these throughout the measurement period. Upon closer reading of the document, it was found that this has been a false assumption and that the tanks may take on any temperature set-point of the user's choosing.

7.5.1 Heating Unit Properties

In order to test the unit's ability to supply hot water at the temperatures and flow-rates described in this and in previous generations of this project, the physical properties of the heating units must be evaluated.

The ability of the heating system to provide desired temperature and flow outputs is dependent on the power output of the heating elements (Q) and the ambient temperature (T_0) of mains supply water entering the system. It is granted that energy losses to the atmosphere will prevail as a result of cooling (W_s) although since the Rheem units are adequately insulated these losses are of little significance. Energy entering and exiting the system can be easily accounted for by the energy balance in Equation 9 whereby accumulation is a result of energy in minus energy out. At steady state temperature, the rate of energy accumulation should be zero.

$$\text{Accumulation} = \text{heating element} + \text{entering fluid} - \text{exiting fluid} - \text{losses}$$

$$V\rho C_p \frac{dT}{dt} = Q + \rho C_p F T_0 - \rho C_p F T - W_s \quad (9)$$

Heated Supply Tank Energy Balance

The heaters are fully sealed, hence completely full at all times, no mass accumulation occurs, given the assumption that under steady-state conditions no change in water density occurs. With an inlet flow-rate of 3l/min and an approximate ambient temperature of 19°C, the amount of energy supplied by the heating element to maintain steady state temperature can be calculated. If the heating element is unable to provide enough power to balance the energy exiting via the inlet stream, then the temperature within the tank will fall below the required value.

A series of tests were conducted in order to quantitatively determine the maximum power output of the cold/hot tank heating elements. In these trials, both tanks were operated at various duty cycles while no liquid entered or exited the units, and with the circulation pumps enabled to ensure adequate mixing. By observing the rate of temperature increase within the tanks a good representation of how much power is supplied by the heating elements is achieved. Table 5 displays the rate of change of temperature per second value for both heating units and the power output at various duty cycles. Equation 10 outlines the method used to produce these results.

$$Q = V\rho C_p \frac{dT}{dt} = 50L * 0.978 \frac{kg}{L} * 4.191 \frac{kJ}{kg.K} * \frac{dT}{dt} \quad (10)$$

Power Output of heater based on temperature rate of change

	Cold Tank		Hot Tank	
DC %	$\frac{dT}{dt} (\frac{K}{s})$	Heating element output Q (kW)	$\frac{dT}{dt} (\frac{K}{s})$	Heating element output Q (kW)
25	0.0085	1.742	0.0131	2.685
50	0.017	3.484	0.0263	5.39
75	0.0253	5.185	0.0391	8.013
100	0.034	6.968	0.0522	10.698

Table 5 Heating unit Power output vs. Duty cycle (DC)

The relationship between heating element duty cycle (DC, %) and power output (kW) is represented in Figure 11. Note that although the rated output for both heaters is 14.4kW, the experimental maximum value falls short with 7.09kW and 10.88kW for the cold and hot tanks respectively. The discrepancy appears to be too large to be caused by measurement or parameter estimation (V , ρ and C_p) error and is rather more likely to be a consequence of not all three heating elements within the cold tank being connected and variation in three-phase power being supplied to both units.

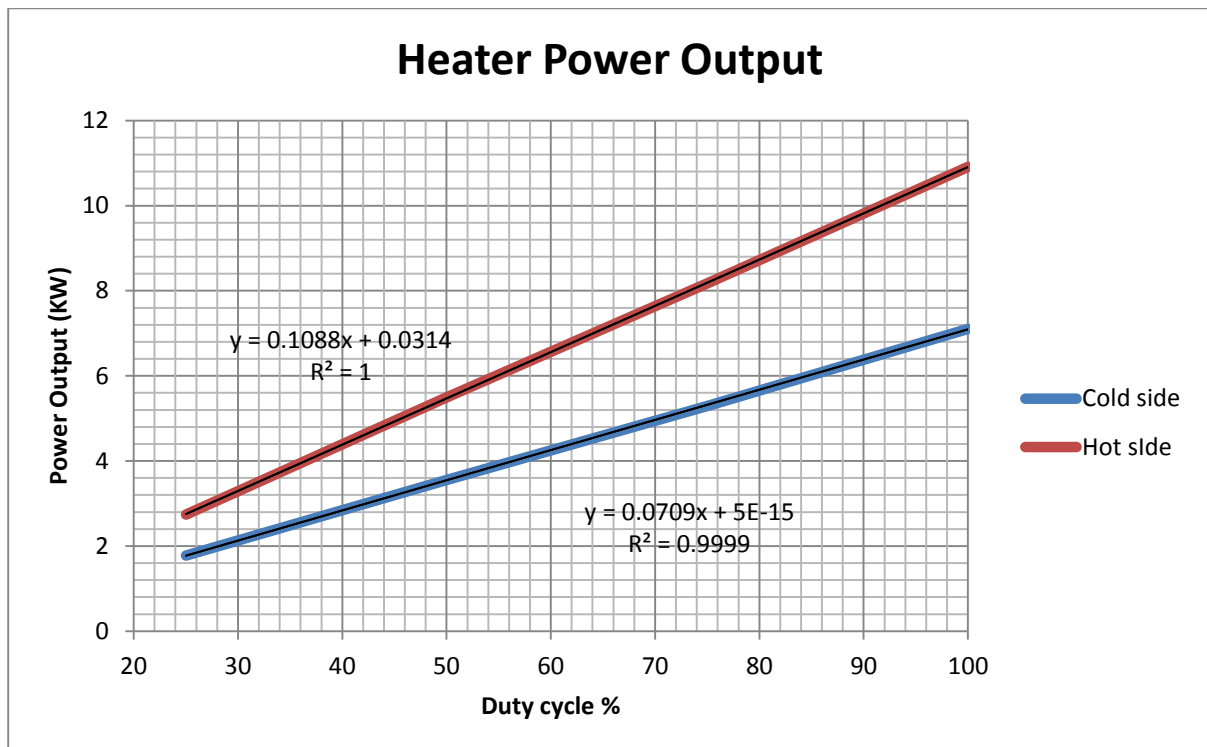


Figure 11 Heater Power vs. Duty Cycle

7.5.2 'Over-temperature' Safety Cut-off

In 2009 and 2012 it was concluded that the hot water supply unit is not capable of providing water at temperatures above 65°C at a stream flow-rate of 3 l/min. Throughout testing carried out by Moussa and Al Asi, a phenomenon occurred where the temperature within the tank would decrease gradually from 70°C whilst outputting 3 l/min (duty cycle 100%), then suddenly drop severely for a number of minutes. Following this event, the temperature within the tank would then begin to rise once more. This event appears more pronounced with the circulation pumps disabled, hence proper mixing is likely to not be achieved.

After viewing this effect, it was hypothesised that the periodic rise and fall in temperature was a result of poor mixing of the circulation in the tank. Without proper mixing, cold water would enter at the bottom of the unit and only 'rise' through the unit as water higher in the tank passed through the outlet. The supposed inability of the heating element to provide enough power to sufficiently heat the water at this high flow-rate (3 l/min) made this a possible cause of the sudden drop in temperature and subsequent increase.

The phenomenon was able to be replicated and is shown in Figure 12. Analysis of the test conditions found that, with the heater duty cycle at 100%, 3 l/min out flow, and circulation pump off, the temperature within the hot supply tank would rise and fall over a period of approximately 22 minutes Figure 12. Note that the temperature is taken at the outlet and therefore does not represent the temperature throughout the entire column of water.

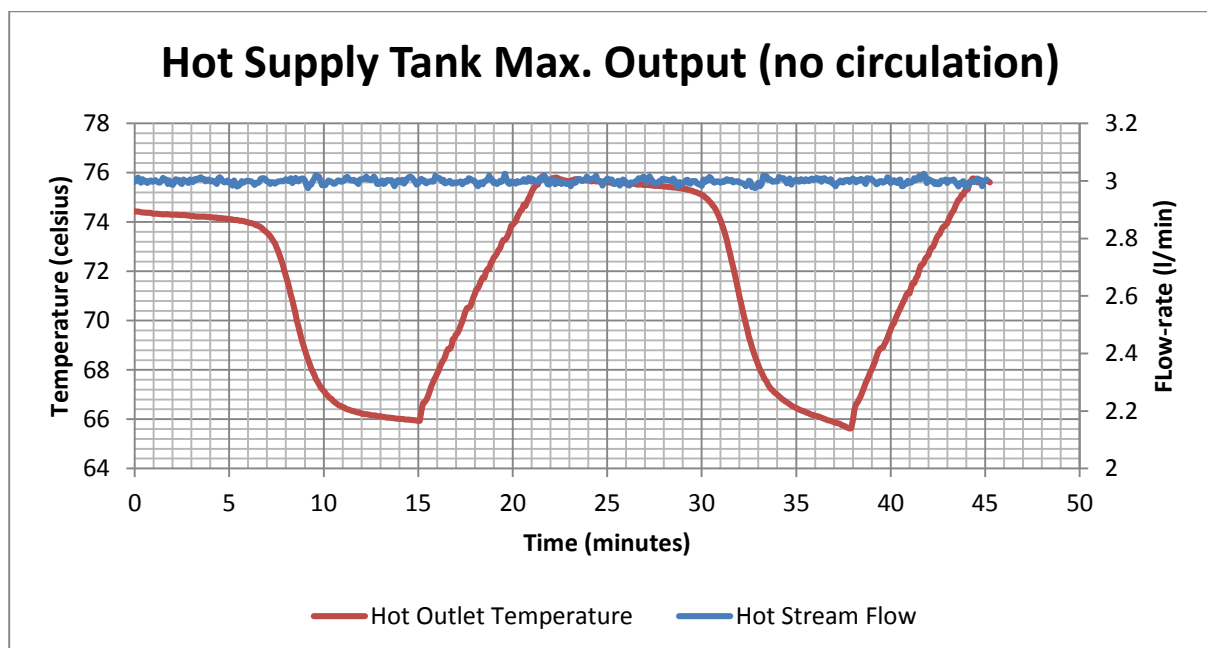


Figure 12 Max Hot supply tank output (pump off)

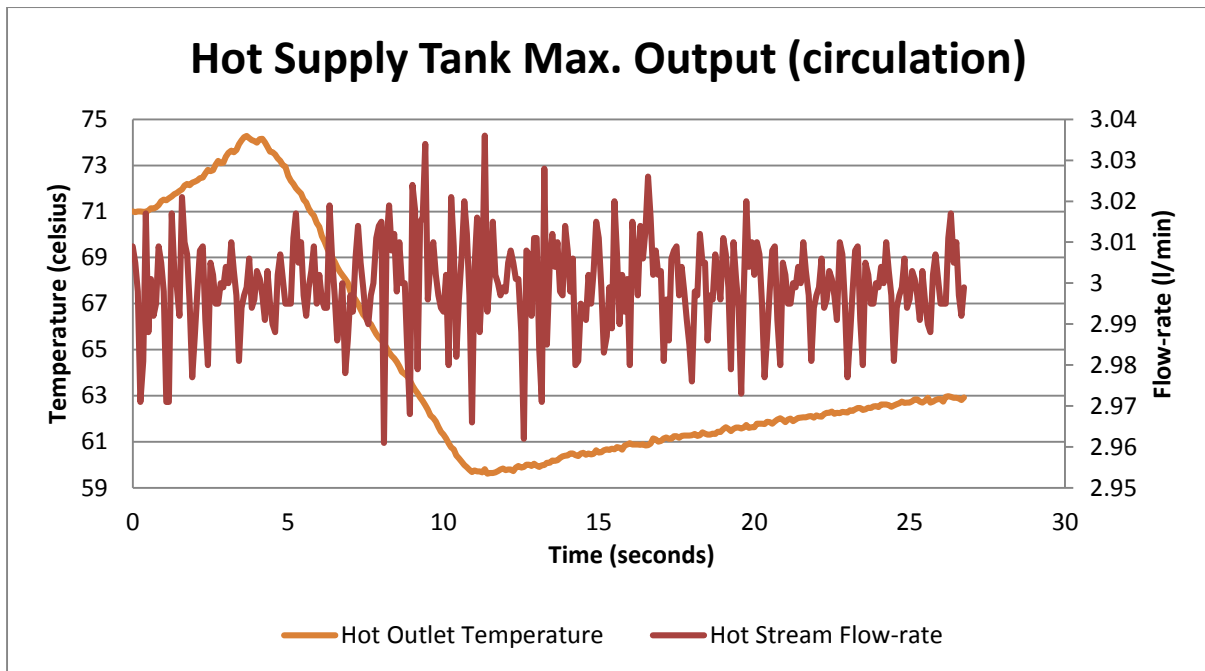


Figure 13 Max Hot supply tank output (pump on)

Figure 14 shows that after water flow through the heater is reduced to 0 l/min, meaning that no energy leaves the tank via transportation of water, the temperature continues to decline although the heating element duty cycle still remains at 100% with circulation on. This indicates that a mechanical interlock on the heating element remains.

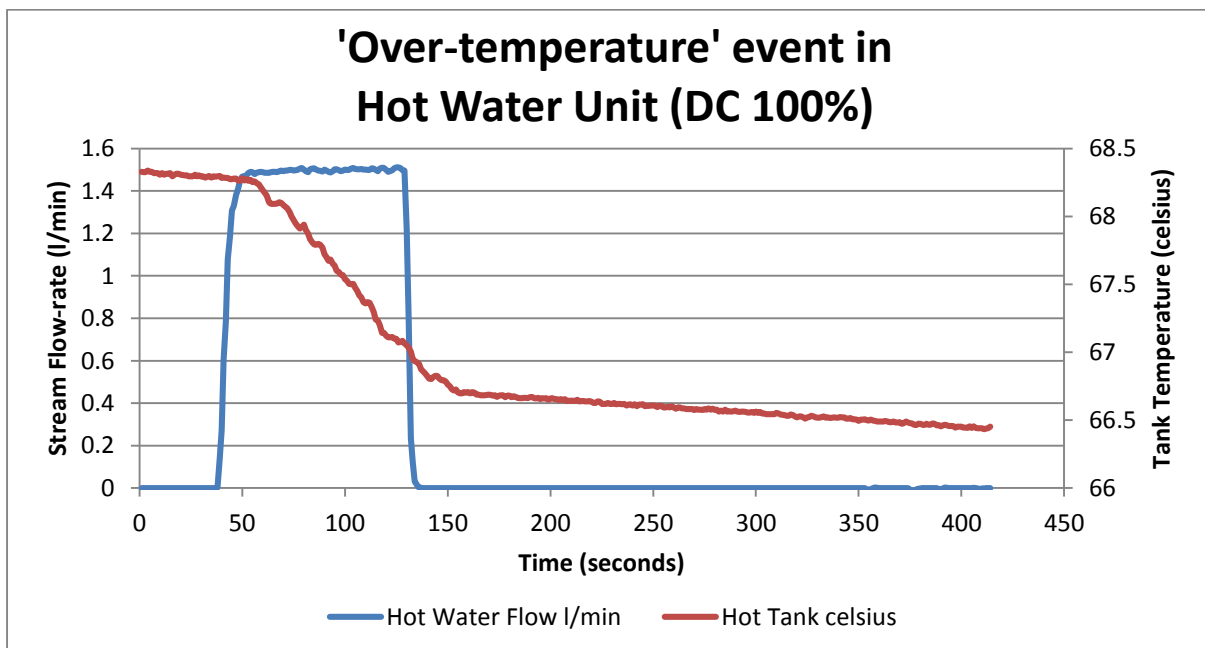


Figure 14 Over-temperature event: No increase in temperature is seen

8. Results

8.1 GMC Heater Disturbance Rejection

The ability of the hot water tanks to reject disturbance in stream flow-rate whilst under PID and GMC control schemes was tested. Due to the length of the measurement period (15 minutes), it was important that the temperature within the supply tanks did not fluctuate too greatly such that the decoupled stream flow-rate set-points would need to change suddenly. The existing PID controller, with tuning parameters $K = 70$ and $\tau = 20$ min, had been used throughout previous iterations of the project and appeared to yield good results, although analysis of the control scheme was not conducted.

The issue with PID control on the water heaters is that that a deviation in process variable must occur before any control action is taken to reject the disturbance. The slow dynamics of the water heating system makes this undesirable since it is a matter of minutes before the process response to the change in control action. Observe Figure 15 where the process variable oscillates as the system responds to the periodic fluctuation of the hot stream flow-rate between 0 l/min and 1.5 l/min. The increase in flow-rate causes the temperature within the vessel to drop as the rate of energy leaving the system rises. In order to compensate for the drop in temperature, the duty cycle of the heating element also increases. When the flow-rate drops to 0 l/min, the lag in heating due to the slow dynamics of the systems allows the temperature to rise; hence a decrease in duty cycle results.

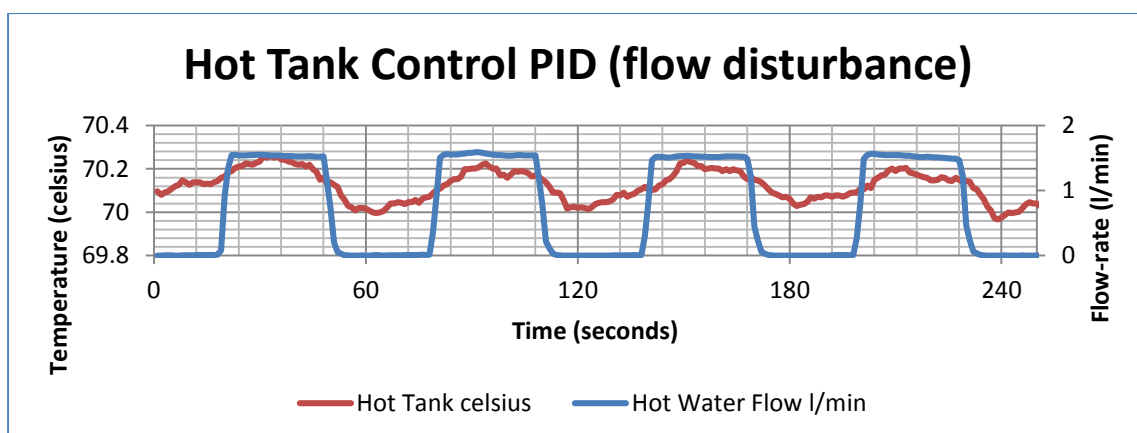


Figure 15 PID Disturbance Rejection

Figure 17 shows the resulting rise and fall of the heating tank duty cycle (MV), PID control, as the disturbance takes effect. Notice that the MV gradually changes in response to the deviation in process variable, hence over-shooting the set-point occurs since the controller has limited 'knowledge' of the systems dynamics. The advantage of Generic Model Control is that the controller is able to both directly and indirectly monitor disturbances to the system.

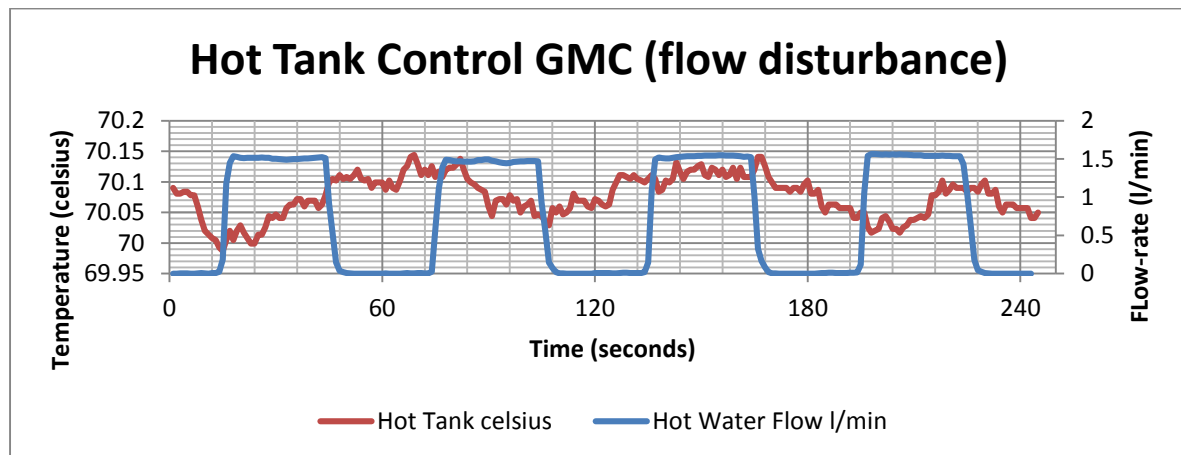


Figure 16 GMC Disturbance Rejection

The result of the same disturbance rejection testing yet under the GMC scheme is shown in figure 16 the GMC controller is better equipped to sense the change in flow-rate and hence instantaneously reduce the heater duty cycle. At 0 l/min it is expected that no energy leaves the tank via the stream, hence the duty cycle drops to zero to prevent any further increase in temperature, as shown in Figure 17. A periodic fluctuation in temperature is still observed in the supply tank, but this appears to be a consequence of the position of the heating elements half-way up the tank causing non-uniform heating of the water column.

A total deviation of 0.217°C in the process variable was observed for the PID scheme and 0.105°C for the GMC scheme. Although this does not appear to be a substantial difference, it did have a greater effect when stream flow-rate above 2 l/min were used. It was of greater importance to reduce the frequency of the fluctuations as it caused the decoupler block and temperature offset controller to adjust more frequently. It ideal that the stream-flow-rates remain as constant as possible.

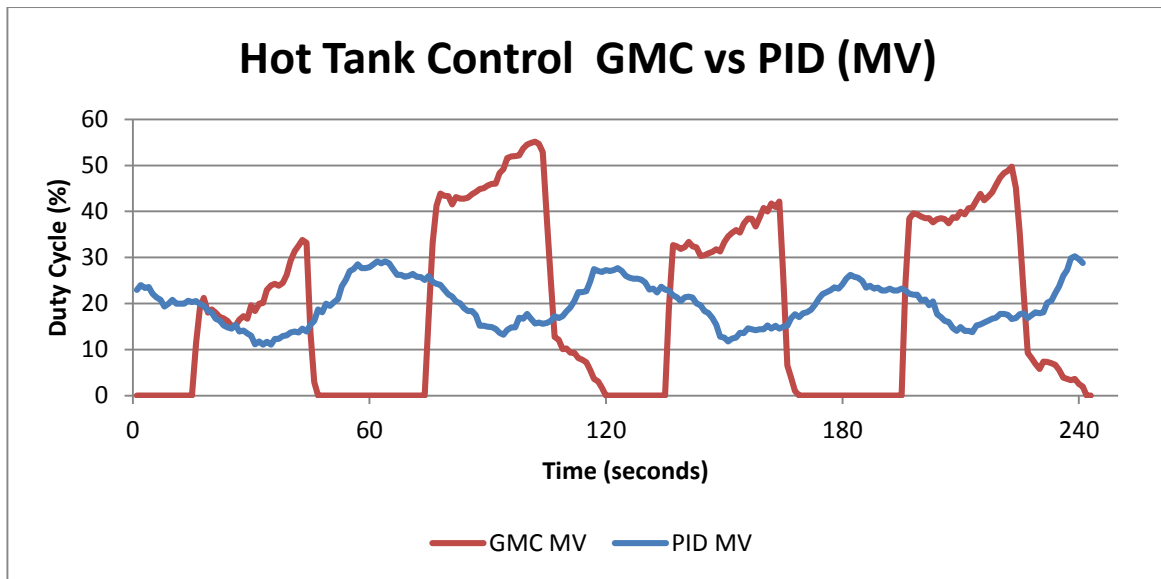


Figure 17 Control-action taken by PID and GMC controllers on Hot supply tank

Testing of the GMC control scheme upon the cold-stream tank was also carried out, yet there was little difference observed between control under PID and GMC schemes. Due to the lower temperature set-point of 30°C being closer to the temperature of ambient water (approx. 19°C) entering the tank, less deviation in the process variable was observed when the stream flow-rate suddenly increases.

8.2 Steady-state Performance Testing

As previously mentioned in section 6.2.2, it has been difficult to reproduce results from 2012 due to issues with the supplied LabView program. Attempts to use the Percentage Decoupler block developed by Al Asi yielded poor results extremely dissimilar to those published in 'Solar Collector Efficiency Testing Unit' (Al Asi, 2012). No steady-state operation was able to be obtained, with the process interactions causing the stream flow-rates to oscillate out of control. For this reason, results gathered by Hany Moussa and published in the report 'Solar Collector Efficiency Testing Unit' (Moussa, 2009) will be used as a yardstick for all results obtained through-out this section.

Using the Values decoupler LabView control program supplied by Al Asi, a set of results were collected. Since there was no publication of steady-state data regarding the use of the values decoupler, the system was tested prior to modifications executed in this iteration of the project and with the tuning scheme and parameters coded in the program. These results

were referred to as '2012', although the data was obtained after the completion of the 2012 iteration of the project. Details of the parameters regarding this test are located in Table 6.

Parameter	cold-side	hot-side
Flow PID controller (LabView)		
Proportional Gain	4.1	4.1
Integral time (min)	0.015	0.015
loop time	250ms	250ms
Stepper-motor Program		
loop time	100ms	100ms
steptime	5ms	5ms
left/rightsteps	1120	1130
adjustlimit	20	20
MaxResult	960	960
Supply Tank PID controller		
Proportional Gain	20	70
Integral time (min)	10	20
loop time	250ms	250ms
set-point	30°C	70°C

Table 6 2012 system parameters

Parameter	cold-side	hot-side
Flow PID controller (LabView)		
Proportional Gain	15	16
Integral time (min)	0.02	0.015
Derivative Time (min)	0.008	0.002
loop time	150ms	150ms
Stepper-motor Program		
loop time	50ms	50ms
steptime	5ms	5ms
left/rightsteps	456	456
adjustlimit	10	10
MaxResult	1123	1123
Supply Tank GMC controller		
Scaled output	7.5kW	10.5kW
K1	10	20
K2	250ms	250ms
set-point (2013)	30°C	70°C
set-point (adjusted stream)	30°C	60°C

Table 7 2013 system parameters

The parameters used throughout the entirety of ‘2013’ tests are located in Table 7. A number of tests were conducted with the ‘cold’ and ‘hot’ supply tanks set to 30°C and 60°C, respectively. These are referred to as ‘2013’ results. Another set of tests with supply tank temperatures of 30°C and 60°C were also executed after it was determined that the ‘over-temperature’ switch issue would prevent higher temperature values from being achieved. These are referred to as ‘2013 adjusted stream’ results.

8.3 Inlet Flow-rate Performance Testing

For the purpose of analysis, the flow-rate and temperature performance are split into individual sections. The first section will evaluate the ability of the controllers to maintain the inlet flow-rate between the deviation limits $\pm 1\%$. A brief description of the statistical metrics used are included in appendix 13.1.

2009 Inlet Flow-rate 3 l/min			2012	
	30°C	45°C		50°C
mean	2.998	2.999	mean	3.00000
mode	2.997	3.001	mode	3.001
st dev	0.014	0.018	st dev	0.00979
ISE	N/A	N/A	ISE	0.11085
max	3.043	3.037	max	3.035
min	2.953	2.94	min	2.959
range	0.09	0.097	range	0.076
violations	23	30+	violations	8

Table 8 Inlet Flow-rate Previous Results (Moussa, 2009)

Table 8 shows a number of statistics regarding the measurements obtained experimentally when testing the previous system. Notice that the measured values obtained by the 2012 unit are marginally improved, with an average reduction of 0.011 l/min in range and a vast reduction in ‘violations’ where the parameter limits are exceeded. The narrower maximum and minimum range also indicates that the 2012 unit could better reject sudden fluctuation in supply pressure. The standard deviation was also improved, indicating that the inlet flow-rate deviated less from the set-point.

2013 Inlet Flow-rate (3 l/min)			
	45°C	50°C	55°C
mean	3.0004	3.000376	2.99733
mode	3.001	3.004	3
st dev	0.00846	0.008272	0.011429
ISE	0.059924	0.06387	0.071387
max	3.034	3.034	3.045
min	2.975	2.974	2.953
range	0.059	0.06	0.092
violations	1	1	7

Table 9 Inlet Flow-rate test 2013

A comparison of 2013 unit results with those in 2009/2012 indicate a better ability to reject the effects of supply pressure fluctuation due to the substantially reduced number of ‘violations’ experienced. A reduction from 30+ to just 2 or 3 per measurement period came as a result of limiting the valves range and tuning the stream PID controllers more aggressively (addition of a derivative term and higher gain). Some tests experienced a higher incidence rate in terms of the measurement value deviating from the set-point by more than $\pm 1\%$. Tests performed during the middle of the day exhibited more ‘violations’ than in measurement periods after 4pm. This is believed to be as a result of increased demand on water supply throughout the day causing pressure fluctuations in the water supply.

Based on the Integral Square-Error (ISE) values in Table 9, it is shown that less deviation from flow-rate set-points occurs when the cold stream flow dominates the mixed stream. This is due to the improved flow-rate control of the cold valve, due to the linear nature of the flow-position characteristic. At a set-point of 55°C, the inability of the hot stream controller to regulate flow and reject pressure fluctuations resulted in more ‘violations’ and a wider range of values, 0.92 l/min compared to 0.6 l/min. Note that violations of the flow limits were only in the order of 2-5 ml/min (for 45°C and 50°C) which is substantially improved when compared to results from 2009.

2013 'Adjusted Stream' Inlet Flow-rate (3 l/min)				
	30°C	45°C	55°C	67°C
mean	2.999	3.00006	2.9999	3.0002
mode	3.001	3.002	3.002	2.993
st dev	0.011886	0.010854	0.013014	0.014973
ISE	0.127823	0.106144	0.152599	0.202044
max	3.049	3.042	3.049	3.052
min	2.948	2.954	2.958	2.958
range	0.101	0.088	0.091	0.094
violations	0	5	14	0

Table 10 Inlet Flow-rate adjusted streams 2013

Due to the controller's inability to maintain the hot water supply tank consistently at 70°C, tests were conducted with the hot supply tank temperature set-point reduced from 70°C to 60°C. For a maximum temperature data point of 67°C, the hot tank was set at 70°C and the cold tank to the much higher than usual value of 66°C. This steady-state operation of the tank at 70°C was possible because the hot stream flow-rate only reached a maximum value of 0.45 l/min. Hence the tank temperature was relatively unchanged over the 15 minute period. The modification to stream temperature altered the ratio of cold/hot stream flow, and had very little other effect on the control scheme parameters. The modified set-point system has been referred to as '2013 adjusted streams'.

Table 10 displays the results of testing with inlet temperatures of 30°C, 45°C, 55°C and 67°C. Data points were taken at the minimum and maximum values as they fulfil the required temperature range suggested in the Standard (30°C classed as ambient temperature). As the temperature of the hot stream was reduced, this also increased the magnitude of flow required through the stream to fulfil the desired inlet temperature. Originally, for an inlet stream of 55°C at 3 l/min, the cold and hot streams would take on values of approximately 1.5 l/min each. With the reduced hot stream temperature these values are adjusted to 0.5 l/min and 2.5 l/min, respectively. Therefore, it was observed that poorer performance was achieved in comparison to the original stream temperature system due to the poorer performance of the hot stream control valve.

8.4 Inlet Temperature Performance Testing

The steady-state performance of the 2013 system differed greatly to those from previous iterations of the project. In the past it was found that the inlet temperature would tend to fluctuate within a range of 0.5°C which is twice that of the bounds set by the standard. 2013 results showed that the temperature was much better controlled with far fewer ‘violations’ experienced. This is as a result of the new temperature offset controller (see Figure 20) which adds any offset in inlet temperature, T_M , onto the temperature set-point, T_{SP} . Table 11 shows statistics from 2009 and 2012 iterations of the project with respect to control of the inlet temperature, T_M .

2009 Inlet Temperature (3 l/min)			2012	
	30°C	45°C		50
mean	30.003	45.006	mean	49.99
mode	30.006	45.041	mode	49.99
st dev	0.046	0.1	st dev	0.0485
ISE	N/A	N/A	ISE	2.119
max	30.156	45.239	max	50.196
min	29.87	44.729	min	49.803
range	0.286	0.51	range	0.393
violations	30+	30+	violations	20+

Table 11 Inlet Temperature Previous Results

Under the 2013 control strategy, no ‘violations’ occurred throughout testing of the unit for the temperature ranges displayed in Table 12. It was determined that greater fluctuation in temperature occurred when the hot flow-rate dominated the mixed stream. This is due to ‘violations’ in the hot flow effecting the instantaneous blending within the stream, causing the inlet temperature to rise suddenly then return to set-point.

It is unclear why poorer performance was achieved with the hot supply tank temperature set to 60°C, as it was previously assumed that by having the mixed stream temperatures closer less spiking in temperature would be caused.

2013 Inlet Temperature (3 l/min)			
	45°C	50°C	55°C
mean	44.99	50.00	54.99
mode	45.01	49.99	54.99
st dev	0.041	0.0145	0.0223
ISE	1.5197	0.1902	0.4494
max	45.152	50.058	55.057
min	44.864	49.953	54.931
range	0.288	0.105	0.126
violations	0	0	0

Table 12 Inlet Temperature Test 2013

Observe Table 13, where the adjusted stream result for a set-point of 45°C shows a high presence of ‘violations’ and 55°C where a relatively large ISE value of 1.149 is obtained. For minimum and maximum data points, 30°C and 67°C a high level of performance was achieved due to the dominance of one streams flow, hence ‘violations’ were reduced.

2013 ‘Adjusted Stream’ Temperature (3 l/min)				
	30°C	45°C	55°C	67°C
mean	30.00	45.00	55.00	66.99
mode	30	45.01	55.01	66.99
st dev	0.0219	0.022771	0.0371	0.00766
ISE	0.4501	0.521	1.1495	0.0530
max	30.066	45.085	55.102	67.019
min	29.924	44.923	54.909	66.983
range	0.142	0.162	0.193	0.036
violations	0	10	1	0

Table 13 Inlet Temperature Adjusted Streams 2013

Figures 21 to 26 located in appendix 13.3 display 2013 steady-state operation tests.

9. Conclusion

Successive 30 second averages of the data series obtained from the Solar Efficiency Testing Unit control experiment show that a steady-state does exist, yet the minor limit violations are preventing 100% confidence in the unit ability to provide consistent testing conditions. Intermittent 'violations' only violate the limits by a small amount for 2-3 samples at most and are believed to have little effect on the validity of Solar Efficiency measurements.

It has been found that, by reducing the hot supply tank set-point to 60°C, steady-state operation may be achieved over the full 15 minute measurement period without any sudden drop in temperature caused by the 'over-temperature' switching event.

As a result of these findings that it is concluded that the Solar Collector Efficiency Testing unit is able to supply inlet water feed to a flat-plate solar collector for testing purposes for experimental parameters within the ranges 2-3 l/min and 30-67°C.

Steady-state operation under the strict interpretation of the standard has not yet been obtained and is unlikely to be resolved under this interpretation and with the current apparatus. Numerous tests have determined that performance in compliance with the strict interpretation is not possible unless key changes are made to the unit. These recommendations are located in Section 11.

10. Project Outcomes

The aim of this study was to achieve compliance of the Solar Collector Efficiency Testing Unit (SCETU) with Australian and New Zealand Standard AS/NZS 2535.1.2007, through identification and development of solutions to a number of problems experienced in past iterations of the project. Previous recommendations included improving the quality of instrument signals, and synchronisation of LabView and stepper motor control loops. It was determined early in the study that the control system and instrumentation that operates the SCETU required essential modifications in order to meet the project objectives.

In comparison to previous iterations of the project, control of inlet flow-rate and temperature was substantially improved when using the '2013' system. In terms of flow-rate the new system experienced a reduction in average standard deviation (for similar set-points) from 0.016 to 0.0083, and for temperature from 0.073 down to 0.031. 'Violations' of measured values violated the bounds set by the standard endured, yet the frequency of these events was greatly reduced from approximately 30 down to 0-10 per test. It concluded that removal of signal interference, aggressive PID tuning (for disturbance rejection) and re-calibration of the control valve motor are the cause for the improvement in steady-state performance.

The following sections outline the various changes made to the SCETU and how they affected the ability to contribute to the overall performance of the system.

10.1 Data Acquisition System

A 50Hz Software band-stop filter was applied to the signals entering through the Field-Point Analogue Input modules (AI-100/AI-110). With these activated it was discovered that the sample rate had greatly reduced as the sample rate is dependent on the number of channels being filtered. By evenly distributing the signals inputs across both modules (as opposed to seven on AI-100 and one on AI-110, previously), the sample rate was improved from 890 ms to 480 ms.

Shielding and hardware filtering of small signal wires, and isolation of high voltage equipment vastly improved the level of interference present in measurements and analogue current outputs.

Re-calibration of the mixing control valve and stepper-motor has yielded higher quality results, as the desired opening position from the controller is accurately realised by the motor. The increased voltage range of the ADC and refinement of stepper sequence is the main cause of this improvement.

The introduction of the CDAQ NI-9265 AO device increased the quality of the signal sent to the control valve in comparison to that sent by the obsolete AO-200 module.

10.2 Control System

The PID controllers responsible for hot and cold stream flow-rate control were retuned with the addition of a previously omitted derivative term, K_D . The tuning parameters used by Al Asi in 2012 were developed in accordance with the percentage decoupling method and the stepper motors using their maximum range of 1130 steps, hence they were not compatible with the system after hardware and software changes.

The loop time of the LabView program was decreased to 150ms from 250ms in order to maximise the number of control actions sent to the control valves. This was done due to the increased sample rate of the stepper-motor control and the presence of 3 point averaging, which was introduced to counteract interference to the output signal.

The current Rheem hot water supply tank is unable to consistently maintain the temperature at the desired value of 70°C. It is possible to conduct steady-state tests with the existing heating unit, although this demands that the temperature within the vessel be at its maximum possible value at the start of the test. For the remainder of the test it is required for the heating element to be set to a duty cycle of 100%, thus providing maximum power output. The complication with this method is that since the circulation pumps are not in operation, thorough mixing of the tank does not take place, resulting in a temperature differential between the top and bottom of the tank. Water at the bottom where the ambient water supply enters will be cooler than at the top, while the temperature at the top

of the tank can reach temperatures well over 70°C since the heating element is located half way up the unit.

The Addition of the GMC control helped to increase the period and reduce the magnitude of oscillation in the water heaters. This has reduced the amount that the streams must adjust in order to maintain adequate inlet temperature.

11. Recommendations

Compared to previous iterations of the Solar Collector Efficiency Testing Unit project, a higher level of performance has been achieved. In spite of this, the first ‘interpretation’ of steady-state operation within the bounds of Australian and New Zealand Standard AS/NZS 2535.1.2007 is yet to be realised. It is believed that compliance may be possible, although it is necessary to make a number of key changes to the devices and equipment used. Clarification of the definition of steady-state operations according to the standard must also be obtained.

The main issue with many of the recommendations to be outlined in this section is that a bypass of existing safety measures is required, as well as an increase in cost due to the requirement of replacement equipment.

11.1 Hot water supply tanks

Throughout the testing process it was difficult to consistently maintain the heated supply tanks at the desired temperatures of 30°C and 70°C for the ‘cold’ and ‘hot tank’, respectively. The amount of fluctuation in the ‘hot’ supply tank temperature made it challenging to run successive tests, as operation had to be halted whilst the tank returned to the desired set-point. The addition of the GMC controller reduced the amount of time the heating element duty cycle was set to 100%, which was the cause of the ‘over-temperature’ event. Despite this, periods of heater shutdown persisted.

Although it was determined that the performance of the system was improved when the difference between the tank temperature set-points was reduced, there are a number of possible solutions to this heating problem which may be attempted in further iterations of the project if deemed viable.

11.1.1 Bi-metallic ‘overheat’ switch

The major difficulty with the heating tanks was the automatic overheating protection which caused the heating element to be disabled when the duty cycle of the element remained at 100% for an extended period (approximately 7 minutes). The intermediate solution of re-

adjusting the supply tank temperature set-points yielded good results, but in order to obtain the 70°C maximum inlet temperature (at 3l/min inlet flow-rate) mentioned by the standard, the 'overheat' switch must be removed.

The main issue with removing this switch is that if the heating element remains on for too long it may cause damage to the unit as a result of the high temperatures reached. Failure of electrical components, as well as potential boiling of the water within the tank must be avoided: for the sake of safety, it is recommended that a replacement switch be fitted with a higher temperature rating so that temperatures of 70°C at higher flow-rates are made possible.

11.1.2 Circulation pump disturbance

When the supply tank circulation pumps were enabled, a disturbance in the stream flow-rate was caused. Surges in flow caused by the pump made it difficult to maintain consistent performance, as the disturbance took effect faster than the SCADA system was able to realise a deviation in flow-rate. For some tests it may be acceptable to disable these circulation pumps, but in order to ensure thorough mixing of the tanks and accurate tank temperature control, it is important that this issue be addressed.

11.1.3 Addition of temperature sensor on mains water supply

The addition of a temperature sensor will help to improve the performance of the GMC controller, as it is currently assumed that the mains supply water is fed at 19°C. Throughout the day it is expected for this value to fluctuate, and by better evaluating the temperature of flow into the tank more accurate power output can be determined.

11.2 Disturbances in water supply feed

Since the project's initial proposal there have been issues with pressure fluctuations within the mains water supply. The pressure changes make flow-rate control difficult due to the consistency of the disturbance and the inability to accurately measure, and thus predict disturbances. By removing the heated tank directly from the mains supply and buffering the flow using large elevated storage tanks this fluctuation may be removed. The main difficulty is ensuring that adequate pressure exists such that desired flow-rates can be achieved.

11.2.1 Increase sample rate of data acquisition

The current sampling rate of the Field-Point analogue input device is approximately 500 ms regardless of the user-defined loop time selected for the control system. This sampling rate can be reduced if the software filters configured through the Measurement and Automation Explorer (MAX) are disabled. For clarity of measurements and reduction of noise induced in the system, it is necessary that these filters remain in operation. Unfortunately, the current sample rate is not fast enough to detect sudden fluctuation in flow-rate induced by the mains supply pressure disturbance.

Data acquisition hardware such as CompactDAQ is capable of achieving faster sample rates, yet the inability to filter out 50Hz noise is a major drawback and prevented the use of the system for analogue signal readings. CompactRio is capable of faster sample rates and real-time filtering, yet the cost of such a system makes it impractical for such an application.

11.2.2 Repositioning heating tanks

It was noted that the discrepancy in heated supply tank elevation caused a difference in the flow characteristic through the streams. The additional height of the 'cold' heated tank induced higher flow-rates in the cold stream at lower valve positions in comparison to those in the 'hot' stream. The pressure drop due to the additional height therefore effects the tuning of the PID controllers responsible for regulating the flow through the cold stream.

11.3 Analysis of flow characteristic with presence of Solar Collector

During commissioning of the SCETU it may be necessary to test the unit with a solar collector connected. This is as a result of a pressure differential experienced between the collector inlet and outlet connections will ultimately affect the maximum flow-rates possible. It is expected that mains supply pressure will be capable of supplying appropriate pressure such that maximum flow-rates will be within those set by the test criteria.

11.4 Solar Radiation Equipment

Calibration and accuracy regarding solar radiation measurement devices has not been explored and lies outside the scope of this report. In the future, the data acquisition system may require adjustments in order to facilitate these additional measurement devices. The

current Human-Machine-Interface used throughout the project does have front panel indicators already in place in anticipation of such additions to instrumentation.

12. References

- Al Asi, A. (2012). *Solar Collector Efficiency Testing Unit*. Perth: Murdoch University Research Repository.
- Al-Senaid, H. (2007). *Solar Collector Efficiency Testing Unit*. Murdoch: Murdoch University Research Repository.
- Apricus. (2013). *Sollar Collector Efficiency*. Retrieved November 2, 2013, from Apricus: http://www.apricus.com/html/solar_collector_efficiency.htm#.UojNmeIUan9
- Emerson Process. (2012, November). *51000 Valve*. Retrieved from Emerson Process Bulletin: www.documentation.emersonprocess.com/groups/public/documents/bulletins/d103339x012.pdf
- Grigg, J. (2002). The health effects of fossil fuel derived particles. *Archives of Disease in Childhood Vol: 86*, 79-83.
- Gvozdenac, Z. K. (2008). *Applied Industrial Energy and Environmental Management*. John Wiley & Sons, Ltd.
- Hass manufacturing company. (2013, August 3). *EPV-250B owners manual*. Retrieved from Hass: <http://www.hassmfg.com/manuals/epv.manual.pl/1235706283-76982>
- Jian, E. (2006). *Solar Collector Efficiency Testing Unit*. Murdoch: Murdoch University Research Repository.
- Kalogirou, S. (2004). *Solar thermal collectors and Applications*. Nicosia: Higher Technical Institute.
- Merriam-Webster. (2013). *Parameter - Definition*. Retrieved November 15, 2013, from Merriam-Webster: <http://www.merriam-webster.com/dictionary/parameter>
- Moussa, H. (2009). *Solar Collector Efficiency Testing Unit*. Perth: Murdoch University Research Repository.

- National Instruments. (2002, October). *Fieldpoint Operating Instructions: FP-AO-200*. Retrieved October 22, 2013, from National Instruments: www.ni.com/pdf/manuals/323343a.pdf
- National Instruments. (2003, April). *FP-1000/1001 User Manual*. Retrieved August 12, 2013, from National Instruments: <http://digital.ni.com/manuals.nsf/websearch/C414184E2D968D5D86256CEF00010B0F>
- National Instruments. (2013). *Analog output*. Retrieved October 22, 2013, from National Instruments: <http://sine.ni.com/nips/cds/view/p/lang/en/nid/208785>
- National Instruments. (2013). *NI C Series Embedded Measurement*. Retrieved October 19, 2013, from National Instruments: <http://www.ni.com/white-paper/14095/en/>
- Ogunnaike, A. (1994). *Process dynamics, Modelling and Control*. New York: Oxford University Press.
- Rosenberg, L. (2000, October 8). *Motorola 68HC12 User's Manual*. Retrieved from ECSE: http://www.ecse.rpi.edu/courses/CStudio/hc12/M6812_Users_Man.pdf
- Standards Australia. (2007, March 7). *Test methods for solar collectors: AS/NZS 2535.1.2007*. Standards Australia. Retrieved July 29, 2013, from SAI Global.

13. Appendices

13.1 Statistical Metrics

Statistical metrics used to analyse system performance:

- Mean, the sum of all experimental values divided by the number of values;
- Mode, value that appears the most frequently;
- Standard Deviation, amount of variation from the mean.
- ISE, Integrated Square Error;
- Max, maximum value that occurs;
- Min, minimum value that occurs;
- Range, the difference between the minimum and maximum value;
- Violations, number of times the experimental value exceeds the accuracy bounds.

13.2 Valve Step test

Figures 18 and 19 show the result of step tests on control valves used. These step tests were used to develop tuning parameters for each stream at a high range (upper) and low range (lower) flow-rate.

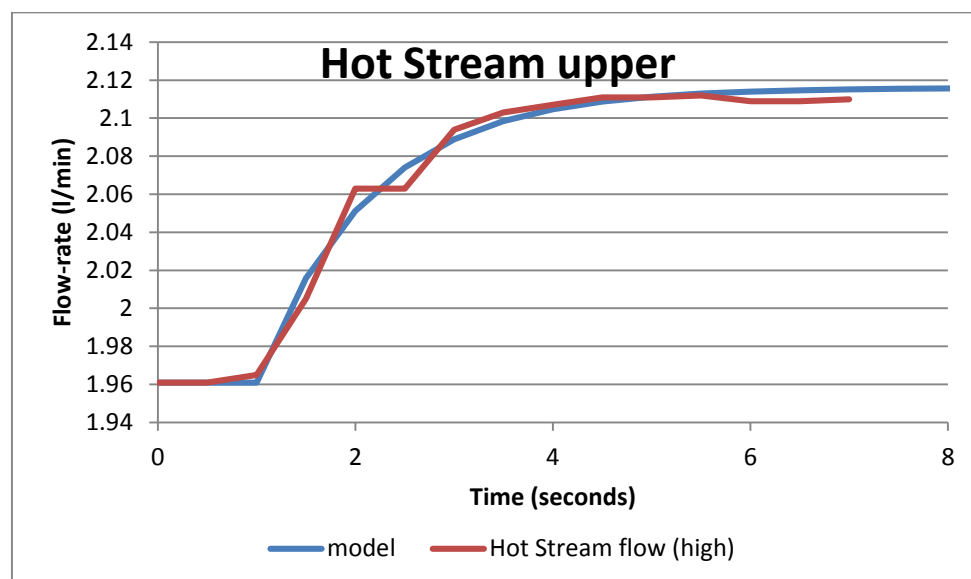


Figure 18 Hot flow model (upper)

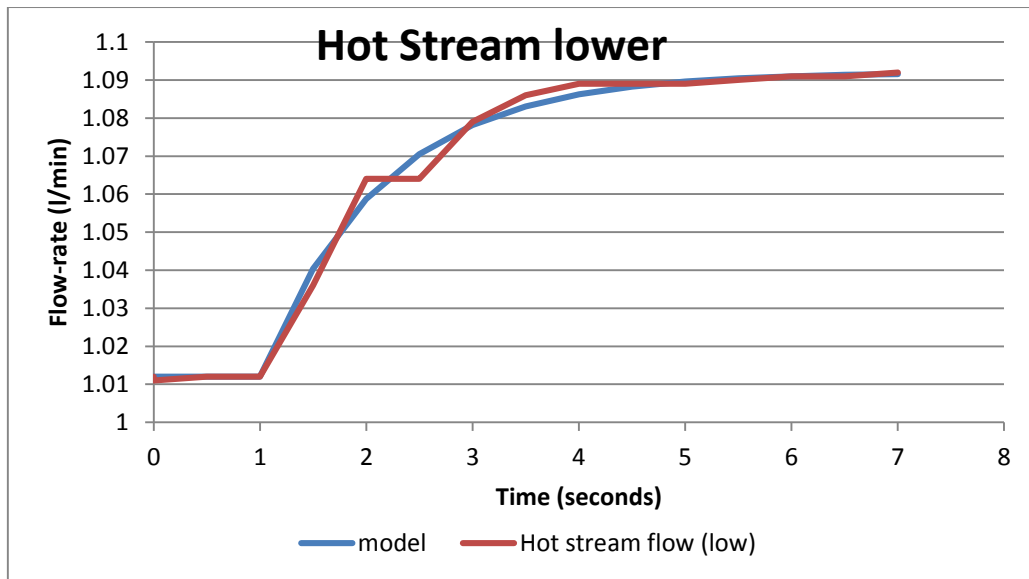


Figure 19 Hot flow model (upper)

13.3 Flow chart for decoupler operation

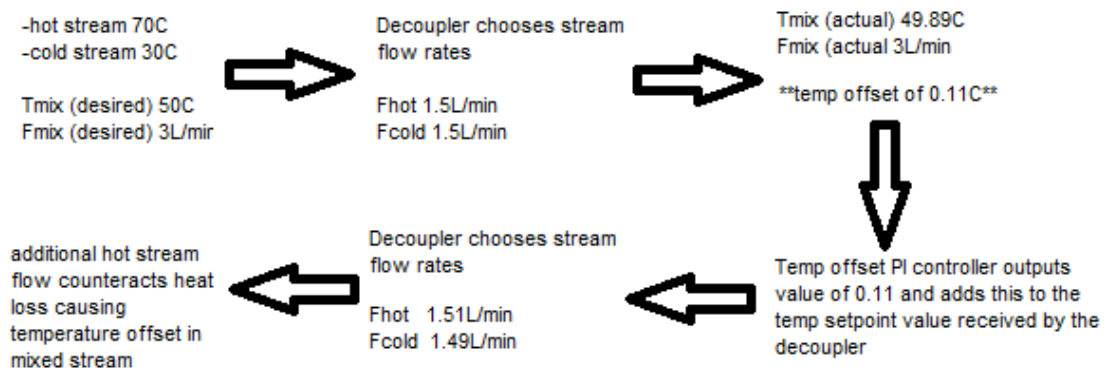


Figure 20 Inlet Temperature: Dynamic response to temperature offset controller

13.4 steady-state test results from 2013 project

Figures 21 to 26 show the Solar Efficiency Testing Unit under steady-state operation. All statistics in the results section are based upon these experimental values.

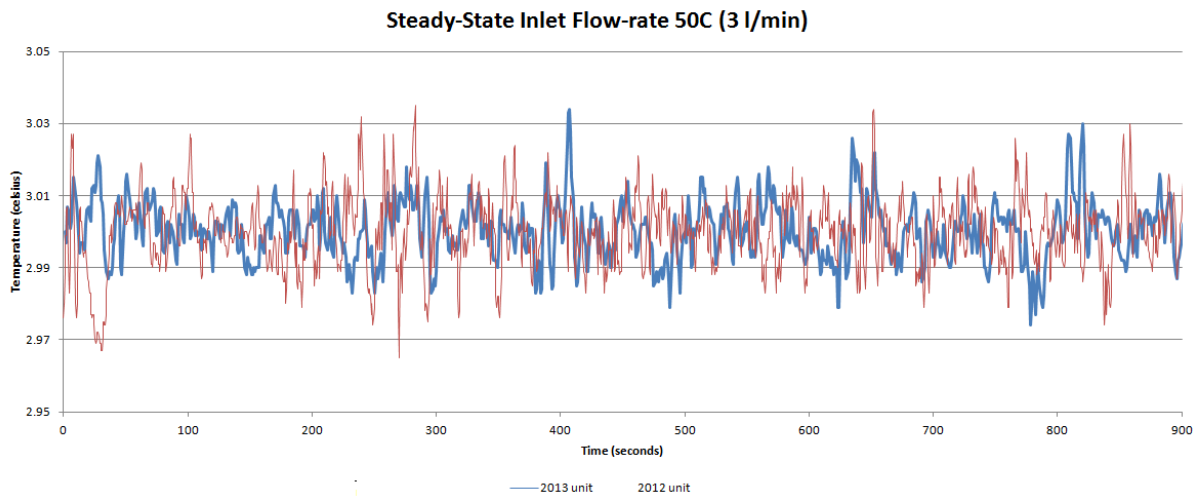


Figure 21 Steady State Inlet Flow-rate for Temperature SP: 50°C and Flow SP: 3l/min

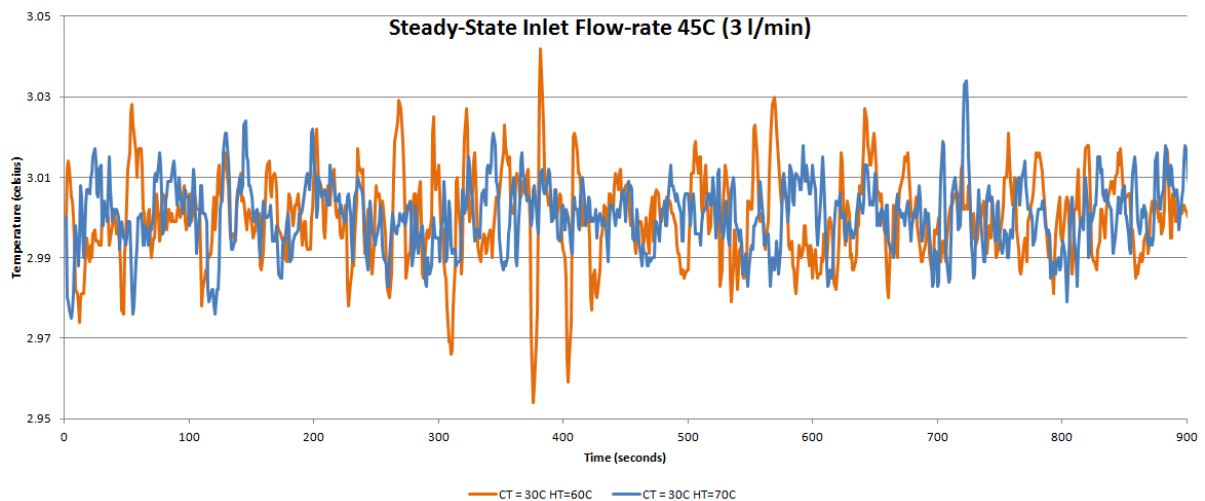


Figure 22 Steady State Inlet Flow-rate for Temperature SP: 45°C and Flow SP: 3l/min

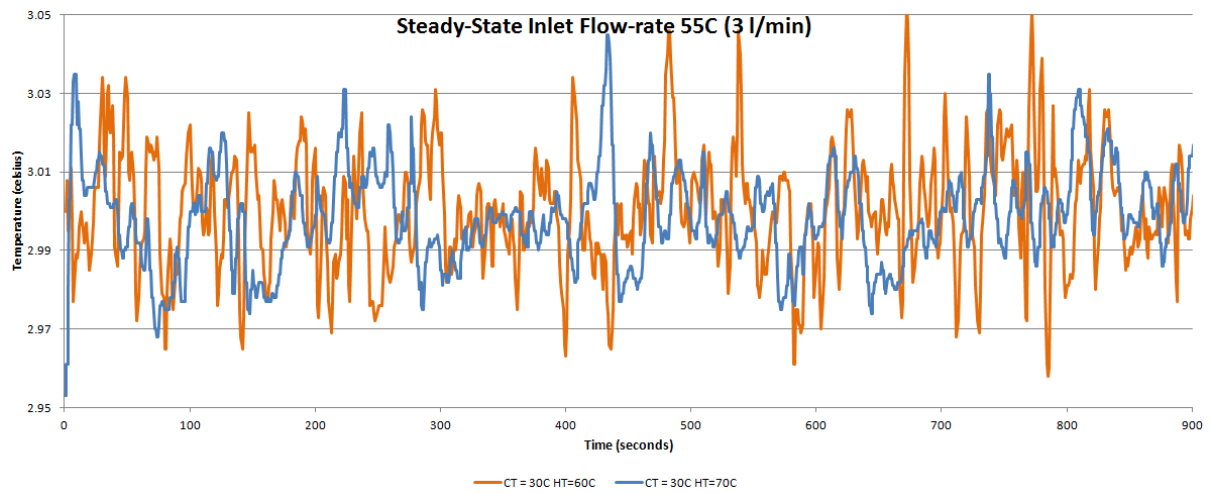


Figure 23 Steady State Inlet Flow-rate for Temperature SP: 55°C and Flow SP: 3l/min

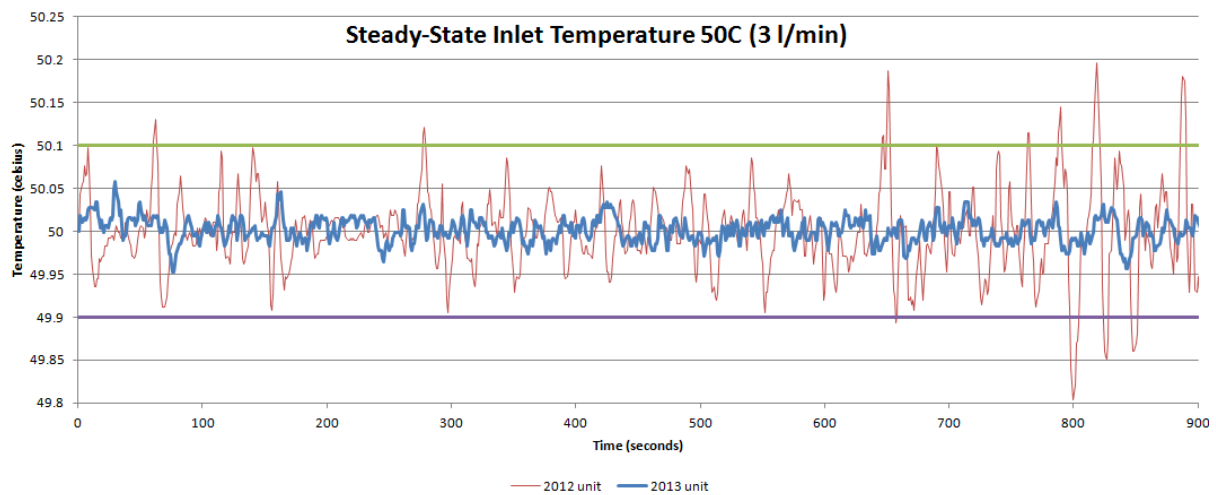


Figure 24 Steady State Temperature for Temperature SP: 50°C and Flow SP: 3l/min

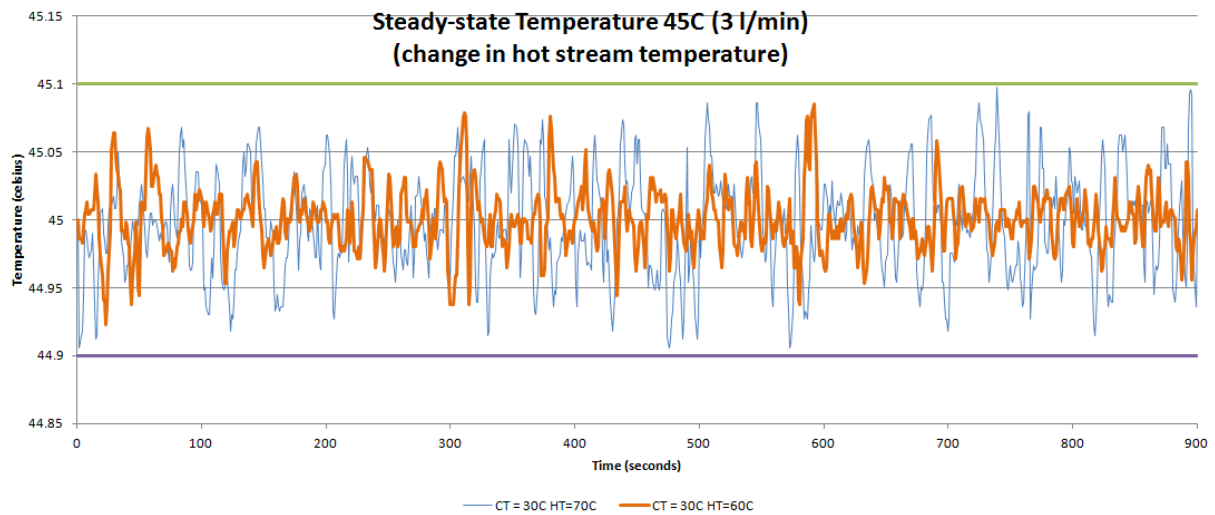


Figure 25 Steady State Temperature for Temperature SP: 45°C and Flow SP: 3l/min

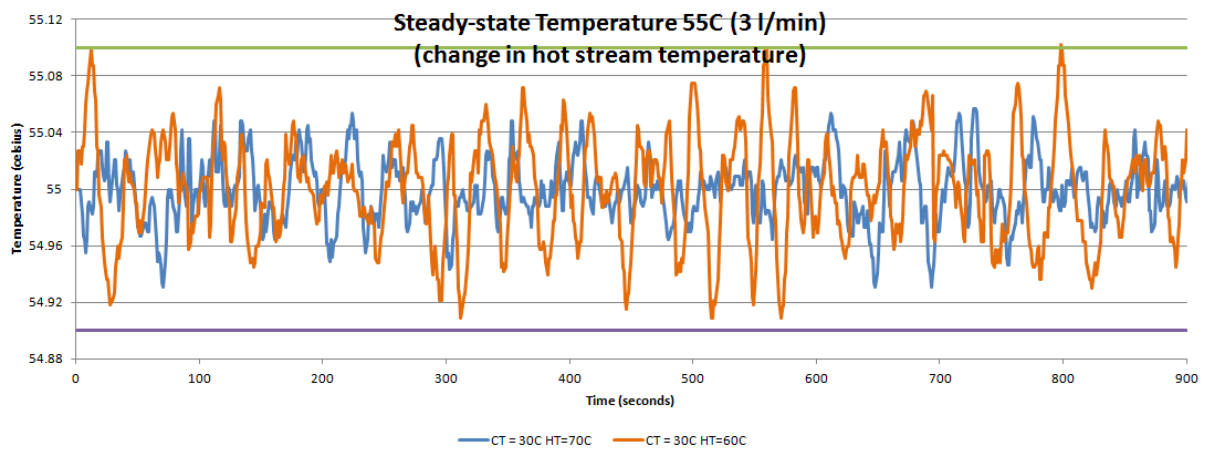


Figure 26 Steady State Temperature for Temperature SP: 55°C and Flow SP: 3l/min